FINAL REPORT

SUBMITTED TO: Naval Medical Research and Development Command
Naval Medical Command, National Capital Region
Bethesda, MD 20814-5044

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TITLE: BIOMEDICAL CRITERIA FOR OPTIMAL ELASTIC RESISTANCE IN DIVERS' UNDERWATER BREATHING APPARATUS

NAVY CONTRACT: PROJECT NO. N0001489J1702

CONTRACT PERIOD: January 1, 1989 - June 30, 1993

Buffalo, NY October 5, 1993

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INTRODUCTION

This project is part of a series of investigations aimed at providing the US Navy with design criteria for acceptable respiratory impediment in divers' breathing gear so as to enhance performance and safety of military divers. Specifically, the present project was conceived to study the effects on divers' respiratory performance by elastic resistance, combinations of elastic resistance and static loading and of flow resistance and static loading. The effects of static load and flow resistance each acting alone have earlier been subjects of extensive studies in this laboratory (Thalmann et al., 1978; Thalmann et al., 1979; Hickey et al., 1987; Norfleet et al., 1987; Warkander et al., 1989; Warkander et al., 1990; Warkander et al., 1992). Elastic resistance may be encountered when breathing on a stiff rebreathing bag (closed and semiclosed gear) or when wearing a tight-fitting, unyielding rubber suit or chest harness; static loading (also known as positive and negative pressure breathing) is the result of differences between breathing gas pressure and mean water pressure on the chest (may be due to depth difference between breathing bag and chest); flow resistance is created in breathing tubes, mouthpieces, CO_2 absorbers etc.

The subjects, who were breathing air, exercised in the prone position. Exercise was performed either on an underwater ergometer or by tethered leg-kick swimming with fins.

The ergometer work was chosen for ease of defining workload and to allow comparison with earlier studies, fin swimming was included as a more realistic type of exercise and to determine how directly the large material we have gathered so far on ergometer work might be applicable to real in-the-sea conditions. In the course of the study, differences between the findings with the two exercise modes were observed which made us suggest more extensive studies of this aspect while reducing the efforts on assymetrical elastic loading. The latter condition was deemed less important since it would be an unlikely scenario under actual diving conditions. Approval by the Submarine and Diving Medicine Program Manager for this modest modification of the protocol was obtained. A few other parameters could not be recorded as originally planned. Thus, carbon dioxide production has not been measured and derived parameters such as respiratory exchange ratio and alveolar ventilation not calculated. The reason for this is technical difficulties with the original, open circuit breathing apparatus. A novel concept for a closed circuit apparatus had to be used as detailed in our Progress Report of August 30, 1990. This apparatus has performed very well, but did not, because of its CO_2 absorber, allow measurement of CO_2 production. The lack of the latter parameter is of marginal importance and does not render the project less useful. In the course of the study, it was found that diaphragmatic EMG recordings did not offer a reliable correlate to CO_2 levels or dyspnea. Hence, we did not continue such recordings throughout the series.

The following 26 parameters were obtained in compliance with the original protocol: vital capacity, forced vital capacity, forced expiratory volume in 1.0 s and peak flow, forced expiratory volume fraction, maximal voluntary ventilation, minute volume, breathing frequency, expiratory reserve volume, tidal volume, end tidal P_{O2} and P_{CO2}, O_2 uptake, maximal inspiratory and expiratory flows, inspiratory and expiratory times, peak and average mouth pressures, maximal voluntary inspiratory and expiratory pressures, power of breathing, pressure-time product, heart rate, three tiered dyspnea score and Borg-scale rating of perceived exertion.

The following activity levels characterize this study:

Experiments under pressure, man hours	1789
Dive experiments, No	243
Man-dives in experiments, No	731
Testing, Training, Treatments*, man hours	56
Testing, Training, Treatment* dives, No	35
Testing, Training, Treatment*, man dives	55

MATERIALS AND METHODS

The subjects in each study were five or six non-smoking males, between 19 and 27 years old, and they were all certified scuba divers. The protocol had been approved by the Institutional Review Board on Human Subjects and Experimentation of the University at Buffalo and the subjects had given informed consent to participate.

The experimental dives were performed in the wet compartment of a hyperbaric chamber system which has been described earlier (Thalmann, Sponholtz, Lundgren, 1978). The technical crew inside the chamber consisted of a safety tender who was positioned in the water within arm's reach of the subject and a tender who controlled the breathing apparatus and the respiratory recording equipment. An intercom system allowed communication between the inside and outside crew. An underwater loudspeaker allowed the outside crew to talk to the subject.

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* Except for one case of skin bends which responded well to treatment, no adverse effects of the experiments were noted.

Exercise was performed submersed in the prone posture at a workload corresponding to 60% of each subject's maximum oxygen consumption (as determined when sitting upright on a cycle ergometer in air at 1 ATA.). Exercise was either performed on an underwater cycle ergometer (Collins Inc., Braintree, MA, modified for underwater use or by tethered fin swimming.

The subjects were breathing air. The breathing gear consisted of a full face mask (modified AGA Divator, Interspiro Inc., Branford, CT) with an oronasal cup. The dead space in the oronasal cup was about 75 ml (Norfleet, Hickey, Lundgren, 1987). Pressure swings in the mask were measured by a pressure transducer (Validyne DP15, Northridge, CA). Static breathing gas pressure was equal to the water pressure at a plane 7 cm dorsal to the sternal notch (no static load).

The subjects were breathing on a closed circuit breathing apparatus (Fig 1). This functioned as follows: The subject was wearing a full face mask (1). One-way valves (7) and (8) directed the expired air to the CO_2 absorber (4) and then to the bellows (5) or (6) from which the next inspiration was taken. The tension on the springs (9) and (10) imposed the elastic loads. Spirometric recordings of breathing volumes were obtained by signals generated by potentiometers (18) and (19) attached to the movable plates of the bellows (5) and (6). The breathing gas was sampled at (13) and analyzed by a mass spectrometer from which a signal proportional to the O_2 fraction was fed to the controller (14) which adjusted the flow of make-up O_2 through the mass flow regulator (15) to the inlet (16). Mixing of the make-up O_2 and the air was enhanced by letting the O_2 in through the mixing hoses (17). The selector valves (20) and (21) allowed rapid switching between breathing against an elastic load and free breathing of chamber air.

The bellows (5) and (6) were placed on the dry side of the Lanphier-Morin barrier in the chamber; the CO_2 absorber was placed partly immersed (for temperature control) and the face mask (1) and its connecting hoses (2) and (3) were submersed.

The tension of the springs (9) and (10) on the bellows was calibrated in separate experiments by the use of an electronic pressure transducer and a large calibrated syringe which allowed injection and withdrawal of breath-sized gas volumes. Due to differences in the compliance of air at the two depths, two different sets of springs were made and adjusted for each of the four loads (0, 7, 14 and 21 cm H_2O/L).

The CO_2 absorber was designed to impose very low flow resistance. Since this absorber was not going to be carried by a diver we did not have any weight or size restrictions. The flow resistance for the absorber for air at the greater depth was 0.6 cm H_2O per L/s at a flow rate of 8 L/s.

The bellows (6) provided the final challenge load. The subject could be connected to this load by turning the selector valves (11) and (12). The spring tension of this bellows was set to give an elastic load of 30 cm H_2O/L.

The carbon dioxide in the inspired gas was monitored during the dives and was less than the concentration (0.04%) found in atmospheric air.

Signals from the bellows were displayed on a Grass Polygraph and divided such that one channel represented respiratory volumes directly while the other channel was electronically differentiated to display respiratory gas flow. End-tidal P_{O2} and end-tidal P_{CO2} were determined from samples taken continuously by a catheter located in the oronasal cup and connected to a mass spectrometer (Perkin-Elmer Model 1100, Pomona, CA). The time of inspiration and expiration were calculated from the spirometer trace. Expiratory reserve volume (ERV) was determined from the spirometer trace by requesting the subject to exhale to residual volume at intervals during the experimental run and comparing this volume on the spirometer trace with his preceding end-expiratory volume.

The subjects provided dyspnea scores by hand signals every 5 min throughout a run: a closed fist indicating no shortness of breath, one outstretched finger indicating a feeling of dyspnea not strong enough to make the subject doubt his ability to continue for another 5 min, two fingers indicating dyspnea pronounced enough to make the subject doubt his ability to continue for another 5 min and three fingers for severe dyspnea necessitating immediate termination of the experiment. In the latter case dyspnea scores that were subsequently missed were assigned scores of 3 for the purpose of averaging. It should be recognized that the number scale for dyspnea scores from 0 to 3 should not be thought of as being linear and that an averaged dyspnea score may be misleading from the practical point of view. For instance, a mean score of 1 based on three subjects reporting No 1 dyspnea stands for a different reality than a mean score of 1 based on two No 0 and one No 3 score. The averaging of scores provided a way of crudely illustrating tendencies.

After the chamber was pressurized the subject entered the water and rested for five minutes. Determinations of VC, FEV, and MVV were performed before the subject started exercise. Having exercised for 25 minutes the subject was connected to the final challenge load. He remained connected until he was forced to quit but not for longer than 90 s. Challenge loads were only used in the ergometer study and the fin-swimming study. The reason for not using the challenge loads in the RES study was that in the two preceding studies the challenge load did not appear to make a difference in the outcome of the experiments with the lighter and heavier elastic loads. The reason for this might have been that the subjects, for safety reasons, only were exposed to the challenge load for the last 90 s of an experimental run. Each experiment was divided into 5-minute periods in which parameters related to ventilation were sampled for at least *one minute*. At the same intervals one dyspnea score was obtained (except during rest) and one vital capacity and one maximum pressure maneuver were performed.

The criteria for premature termination of an experiment were that the end-tidal PCO_2 exceeded 65 mm Hg (8.7 kPa) or that the subject did not coöperate adequately. In addition, the subjects were free to terminate the experiment at any time.

Work of breathing against the imposed elastic loads was calculated separately for inspiration and expiration from the mouth pressure and volume signals ($\Sigma P \cdot dV$). As outlined by Morrison and Reimers (1982) only positive work was included in the calculations (i.e. when the product of pressure and volume was greater than zero). Work of breathing per liter of V_t (volume-weighted mean pressure, WOB_{tot}/V_t, where WOB_{tot} is the sum of inspiratory and expiratory work of breathing) was also calculated.

All recordings were stored on tape by an FM-recorder (Honeywell 101, Honeywell Inc., Denver, CO). Reduction of data was largely performed on a computer by programs written in-house. Signals were sampled at 100 Hz.

Statistical analysis was by means of analysis of variance for deviations from control values with Newman-Keuls test. Each subject served as his own control. Significance was noted at $p<0.05$.

RESULTS

The results will, for the most part, be presented in three sections referring to the **ergometer-study** which describes studies of elastic loading with cycle ergometer exercise, the **fin-study** which deals with elastic loading with fin swimming and the **RES-study** which combined marginally acceptable static lung loading with either elastic loading or with flow resistance, while performing ergometer exercise.

Because of the modest number of subjects in these studies the retention of subjects from one study to the next was a concern. Therefore, one of the criteria in the subject selection was the likely continuation into the next study. In the fin-study three out of five subjects were retained from the ergometer-study and in the RES-study four out of five subjects were retained from the fin-study.

Parts of the results described below have been published and presented at scientific meetings as the results became available (Warkander & Lundgren, 1992A; Warkander & Lundgren, 1993A & 1993B).

Elastic Loading with Cycle Ergometer Exercise (Ergometer Study)

Six subjects participated in this study. Their mean age was 22 years. Numerical results and levels of statistical significance are presented in Tables I-IV and graphic presentations in Figs 2-9.

End-tidal carbon dioxide

The two highest elastic loads caused slight increases in the group means of the end-tidal CO_2 levels during exercise at the greater depth (Fig 2). In no other condition did the elastic load affect the CO_2 levels.

It is noteworthy that during exercise the increase in depth *per se* caused increases in $P_{et}CO_2$ of between 5 and 10 torr.

Dyspnea

No dyspnea was reported during resting conditions. During exercise the dyspnea scores increased with increasing elastic load at both depths, reaching statistical significance with all three loads at the shallow depth and with the two highest loads at the greater depth (Fig 3). There were large differences between the subjects. For instance, extreme dyspnea forced subject A to abort his experiments prematurely when exposed the highest load at both depths. Under the same conditions subjects C and D did not report any dyspnea.

Breathing difficulty

The Borg-scale ratings of breathing difficulty were increased with each load at both depths (Fig 4).

Ventilation

The ventilation ($\dot{V}_E$), (Fig 5) was not influenced very much by the elastic loads. The only change was a slight increase by the highest load during exercise at the shallow depth. However, changes were seen in both tidal volume (Fig 6) and breathing frequency (Fig 7). During exercise the elastic loads caused the tidal volume to decrease (by up to 25%) and the breathing frequency to increase (by up to 40%). At rest, the same pattern was seen with all loads at the greater depth and with the highest load at the shallow depth.

Maximal voluntary ventilation, which was only measured during rest, decreased with the lowest and the highest loads at the shallow depth but not at all at the greater depth. The effect of depth was to lower the MVV at the greater depth by, on the average, almost 50% compared to the shallow depth. The FEV % was not changed by the added elastic loads.

Lung volumes

The vital capacities (VC) were reduced by all loads during exercise. At rest the same pattern was seen at the shallow depth and at the greater depth the VC was reduced by the two highest loads. On the average, the highest load reduced the vital capacity by about 25%.

A similar pattern was seen for the expiratory reserve volume (ERV). It was reduced by all loads during exercise and by the highest load during rest. On the average, the highest load reduced the ERV by about 25%.

Ventilatory duty cycles

The duration of inspiration relative to the duration of a breath (T_i/T_{tot}) did not change with any of the elastic loads during rest or during exercise at the shallow depth. During exercise at the great depth it showed a small decrease.

Gas exchange

The oxygen uptake (VO_2) was not influenced by the elastic loads during rest nor at the great depth. During exercise at the shallow depth it was increased with all loads, probably because of lower control values for subject F.

Power of breathing and pressures

The external work of breathing per volume (WOB/V) was increased with all loads under all conditions.

The expiratory power of breathing (Fig 8) increased with gradually increasing loads in all conditions except at rest with the lowest load at the shallow depth. The two highest loads increased the inspiratory power of breathing (Fig 9) during exercise at the shallow depth and the highest load did the same during exercise at the great depth.

Mouth pressures during spontaneous ventilation increased with all elastic loads during exercise. At rest, increases were also caused by all loads in the expiratory mouth pressures while increases in inspiratory mouth pressures were caused by the two highest loads.

Heart rate

The heart rate was influenced by the two highest loads during exercise but not at rest. Depth caused a slight reduction during exercise by an average of 77 beats per minute ($p<0.01$).

Elastic Loading with Fin Swimming (Fin-Study)

The mean age of the five subjects was 22 years. Numerical results and levels of statistical significance are shown in Tables V-VIII and graphic presentations in Figs 10-17.

End-tidal carbon dioxide

The results of the end-tidal CO_2 measurements are shown in Fig 10. At 15 fsw the resting levels were consistently around 40 torr regardless of the elastic load; at work there was a significant increase in the $P_{et}CO_2$ with the two highest elastic loads. At 190 fsw no remarkable effects were induced by the elastic load during rest while during exercise the group as a whole showed a small but significant increase from a mean in the control situation of 48.4 torr to 51.5 torr with the highest elastic load.

There were large differences between the levels of CO_2 maintained by the subjects. Subject B had higher levels of CO_2 (reaching almost 60 mm Hg) than any of the other subjects, while subject C had near-normal levels even during the most severe conditions.

Dyspnea

Dyspnea was only reported during exercise, (Fig 11). The scores did not change with the elastic loads.

Breathing difficulty

The Borg-scale ratings of breathing difficulty were increased by the highest load at the shallow depth and by the two highest loads at the greater depth (Fig 12).

Ventilation

During rest a slightly higher $\dot{V}_E$ (Fig 13) was evident at the greater depth (16.8 ± 0.5 SE L/min) than at the shallow depth (14.0 ± 0.3 SE L/min) ($p < 0.05$). However, during exercise the $\dot{V}_E$ at the greater depth (44.2 ± 1.7 SE, L/min) was the same as at the shallow depth (47.3 ± 2.0 SE, L/min) ($p > 0.05$). No systematic effects of the elastic loads were seen. The breathing frequency (Fig 14) was increased in response to the two highest elastic loads both during rest and exercise at both depths (also with the lowest load during exercise at the shallow depth). The tidal volume decreased with all loads during exercise (Fig 15). The same pattern was seen at rest at the shallow depth, while it decreased with the highest load during rest at the great depth.

The MVV was not affected by any elastic load. It was, however, significantly lower (by almost 50%) at the greater depth. Forced expiratory volume after 1 s (FEV1%) showed slight increases with increasing elastic loads. The FEV1% was depressed at the greater depth.

Lung volumes

Vital capacities were depressed both at rest and exercise at both depths. The highest elastic load decreased the VC by about 25%. During exercise at the shallow depth the ERV was decreased by the two highest loads while at the greater depth it was affected by all elastic loads.

Ventilatory duty cycles

The T_i/T_{tot} showed statistically significant but functionally insignificantly decreases (0.49 to 0.47 or 0.48) during exercise at the great depth.

Gas exchange

The $\dot{V}O_2$ was not influenced by the elastic load except by the highest load at the great depth which caused it to be 8% higher on the average, than the unloaded control value.

Power of breathing and pressures

Work of breathing per L of V_T increased with elastic loads in all conditions. During exercise the inspiratory and expiratory power of breathing was increased by all elastic loads. During rest the POB_{ex} (Fig 16) was increased by all elastic loads but the POB_{in} (Fig 17) was only influenced by the highest load. The pressure swings in the mask were influenced by the elastic loads in all conditions.

Heart rate

Added elastic loads had no effects on the HR except during exercise at the shallow depth when the highest elastic load increased the HR. Hyperbaric bradycardia was evident during exercise by changing from 124.9 b/min at the shallow depth to 113.8 b/min at the great depth ($p < 0.05$).

Marginally Acceptable Static Lung Loading Combined with Either Marginally Acceptable Elastic Loading or Flow Resistance during Ergometer Exercise (RES-study)

Five subjects participated. Their mean age was 23 years. Numerical results and levels of statistical significance are shown in Tables IX-XII and graphic presentations in Figs 18-25.

In compliance with the original research proposal's plan, marginally acceptable static lung loads were tried together with either a marginally acceptable elastic load (ES) or a marginally acceptable resistive load:

a) A -10 cm H_2O static loading with a 7 cm H_2O/L elastic load (ES).

b) A -10 cm H_2O static load with a flow resistance that caused an external work of breathing of 1.5 to 2.0 J/L (RS).

End-tidal carbon dioxide

At rest at the shallow depth RS caused a slight hypocapnia (Fig 18). No changes were seen with either RS or ES at rest at the greater depth. During exercise ES caused increases in the group mean at both depths while RS caused an increase at the greater depth. It must be noted that with the ES combination at the greater depth subject G reached levels of CO_2 that were above the abort limit (65 mm Hg). He had to be told to stop and when he egressed from the water he was unaware of the severe CO_2-load that he had been exposed to.

The experiments at rest revealed a slight hypocapnia 36.9 $\pm$ 0.8 SE, mmHg at 190 fsw compared to 15 fsw 41.7 $\pm$ 0.7 SE, mmHg ($p < 0.05$).

Dyspnea

The dyspnea scores (Fig 19) were not affected by either of the load combinations at the shallow depth. However, at the great depth both combinations caused increases in the group means, the RS producing an average slightly above the acceptable (0.5) limit.

Breathing difficulty

The Borg-scale ratings of breathing difficulty were increased by both load combinations at both depths (Fig 20).

Ventilation

The $\dot{V}_E$ (Fig 21) was not changed during rest, or during exercise at the shallow depth. During exercise at the greater depth it was slightly suppressed by both load combinations.

During exercise at the shallow depth the tidal volume (Fig 22) was increased by RS and decreased by ES. At the greater depth during exercise it was reduced by ES. The ES combination caused increases in the breathing frequency (Fig 23) at rest but not during exercise. The RS combination induced a slight reduction in f during exercise at the shallow depth.

The MVV was reduced by RS at the shallow depth. The MVV was reduced by about 33% at the great depth and was not further reduced by either load.

Lung volumes

The VC and the ERV were reduced by ES in all conditions. The RS combination also reduced the ERV and the VC was minimally reduced during exercise at the great depth.

Ventilatory duty cycles

During exercise at both depths the T_i/T_{tot} was reduced by ES and increased by RS. In both instances the changes were small.

Oxygen consumption

The $\dot{V}_{O2}$ was not affected during rest at either depth nor during exercise at the shallow depth. It was slightly reduced by RS at the great depth.

Power of breathing and pressures

The POB_{ex} increased with both loads at both depths during exercise (Fig 24). The POB_{in} was decreased by ES during rest at the greater depth and increased by RS during exercise at the shallow depth (Fig 25). The WOB/V was increased by both loads during exercise.

Mouth pressures were increased by both loads during exercise.

Heart rate

The HR was not changed by either load in any condition.

DISCUSSION

Our criteria for judging if a given external respiratory impediment was acceptable or not were the same as those applied in our studies of respiratory flow resistance (Final Report Contract N00014-86-0106 and Warkander & Lundgren, 1992B). Briefly, they consisted of maximum CO_2 levels and dyspnea levels. The group average of end tidal P_{CO2} should not exceed 55 mmHg (7.3 kPa) and no individual value should exceed 60 mmHg (8kPa). Dyspnea score averages should not exceed 0.5 and individual values should not be higher than 1. These limits were chosen since it was felt that higher values would either endanger the diver or adversely affect task performance.

Applying the acceptability criteria described above to the elastic loads, loads higher than 14 cm H_2O/L were found unacceptable during ergometer work in terms of CO_2 balance (Fig 2) and above 7 cm H_2O/L in terms of dyspnea scores (Fig 3). By contrast, during fin swimming, all loads were acceptable. Thus, at the same $\dot{V}_{O2}$, ergometer work rendered the subjects more sensitive to elastic loading than fin swimming. The reason for this is not clear. A hypothetical explanation would be that the $\dot{V}_{O2max}$ would be greater in fin swimming than in submerged ergometer work. This would have placed the subjects at a more favorable (less demanding) $\dot{V}_{O2}/\dot{V}_{O2max}$ relationship during swimming than during ergometer work since the $\dot{V}_{O2}$ was the same in both conditions. From the practical point of view, the greater tolerance to respiratory impediment during fin swimming than during ergometer work is important since determinations of tolerance performed during ergometer work may be considered relatively conservative and leave a margin of safety for fin swimming which is a common activity under real diving conditions. It is noteworthy that all earlier Navy supported studies in this laboratory on respiratory performance of divers have been conducted with ergometer work.

The data from the ergometer study are presented in Fig 26 to show the distribution of acceptable and unacceptable outcomes relative to work of breathing and ventilation. A boundary zone between 0.8 and 1.0 J/L distinguishing acceptable and unacceptable outcomes of exposure to elastic loads suggests itself. It appears that elastic loading became unacceptable at a lower work-of-breathing level than did flow resistive work in an earlier study (Warkander & Lundgren, 1992B) where the boundary zone was between 1.5 and 2.0 J/L (Fig 27). (Note though, that only one subject was common to the two studies). Possibly the difference just described is due to the fact that the elastic work of breathing per volume increases as inspiration progresses and the work culminates when the recoil of the respiratory organs is the largest. At the same time the respiratory muscles are at less advantageous points on their length/tension curves at the extremes of inspiration and expiration. By contrast, resistive work per volume peaks at roughly 50% of the tidal volume. These relationships are illustrated in Figs 28. Similar considerations apply during expiration on the condition that it is deep enough to proceed past the relaxation volume of the external elastic-load device.

The plots of power of breathing show some remarkable features. Thus, there are large differences between individuals. Compare for instance, subjects D and F who expended about 0.8 W and 2.8 W, in expiratory power (Fig 8, Panel C, 21 cm H_2O/L) and 1.0 and 1.7 W in inspiratory power (Fig 9, Panel C, 21 cm H_2O/L) respectively, while their ventilations were very similar, namely about 75 L/min (Fig 5). This reflects differences in breathing pattern, the tidal volumes of D being about 65% of F's thus requiring less work against the elastic resistance. In this case, not surprisingly, F reported more dyspnea than D (Fig 3). A similar difference is shown by their Borg-scale scores. A different picture is offered by comparing subjects A and D who had about the same inspiratory and expiratory power yields (Figs 8 and 9, panels C, 21 cm H_2O/L) but who reported greatly different dyspnea levels (Fig 3) while their Borg-scale scores were about the same (Fig 4). The possibility exists that the dyspnea scale and the Borg-scale measure different things. This appears to be born out by the lack of correlation between the two scales (Fig 29). Based on the differences in dyspnea scores between the two subjects just mentioned, one might ask if A had weaker respiratory muscles which consequently would be more stressed by the same power output as that of D. However, this is not born out by the recordings of maximal inspiratory and expiratory pressures in the two subjects (Table III). Alternatively, one may look at the ventilatory effect of a certain power expenditure. Subject D, for instance had among the highest ventilatory yields relative to power of breathing and also the lowest dyspnea scores. On the other hand, subject A for instance, who had an average ventilation/power quotient reported among the highest dyspnea scores. Thus, these comparisons do not offer a consistent picture but it is possible that it would improve if alveolar ventilation (not available - see Introduction) could be substituted for overall ventilation when calculating ventilation/power.

By design, the loads in the experiments which combined elastic loading with static loading and resistive with static loading were chosen to each be marginally acceptable. When the combinations were tried they were all found to be unacceptable. That is to say: in the load combinations, the loads acted in an interdependent manner. Put differently: in their action to increase CO_2 or induce dyspnea the loads acted at least partly through the same mechanisms. However, generally the load combinations did not cause large excursions above the acceptability limits for CO_2 readings and dyspnea scores (Figs 18 and 19). An exception was one end-tidal PCO_2 reading in one subject exceeding 65 mmHg. The question arises as to what levels of combined loads are acceptable. This can only be answered with precision if a series of lower loads are tested. However, as a tentative, relatively conservative estimate, we propose that load levels 50% below the ones tested might be acceptable for the combinations tried. Thus, one would accept an elastic load of 3-4 cm H_2O/L or a flow resistance causing a work of breathing of 0.75 - 1.0 J/L in combination with a static lung load of -5 cm H_2O. It furthermore appears safe to predict that one type of load may be increased above 50% if a corresponding reduction is made in the other.

The mechanisms behind dyspnea and respiratory failure are the focus of much interest by respiratory physiologists. While the present experiments were not directly designed to explore those mechanisms, some related observations were made. Thus, is suggestive that dyspnea might reflect respiratory muscle fatigue. However, the indices of respiratory muscle fatigue, viz. maximal inspiratory and expiratory pressures failed to substantiate this notion. Increasing elastic load had no effect on the pressures and, moreover, the subjects' abilities to generate respiratory pressures did not deteriorate as experiments wore on. This is in keeping with our earlier observations using flow resistive loads (Final Report Contract N00014-86-0106 and Warkander & Lundgren, 1992B). Furthermore, in the latter study, we found that flow resistive loads met with essentially two types of reactions from the subjects (during ergometer work). Either they showed a tendency to accumulate CO_2 without suffering dyspnea or they kept near-normal CO_2 levels at the expense of suffering dyspnea (Final Report Contract N00014-86-0106 and Warkander & Lundgren, 1992B). Interestingly, elastic loads induced the same types of responses in the present study using a new set of subjects (8/9) and including all experimental conditions except rest (Fig 30). It follows that there must be a common final path for these, physically very different, types of respiratory impediments to interfere with respiratory performance. Practically important is that the present observations confirm our earlier recommendation that tests of the effects of respiratory impediments must include both subjective evaluation by the subject, such as dyspnea scoring, and measurements of CO_2 levels (Final Report Contract N00014-86-0106 and Warkander & Lundgren, 1992B).

CONCLUSIONS

These conclusions were based on observations in 5 or 6 subjects. The size of the material should be considered when making generalizations.

1. Respiratory elastic loading in excess of 7 cm $H_2O \cdot L^{-1}$ was not acceptable during prone underwater exercise at 60% of maximal oxygen uptake. Higher loads were unacceptable because they generated excessive end-tidal CO_2 levels and/or excessive dyspnea.

2. At an equal oxygen uptake, a given respiratory elastic load during exercise on an underwater leg ergometer is less well tolerated than during fin swimming. Hence, testing tolerance to respiratory impediment while exercising on the ergometer appears to yield more conservative (safer) tolerance limits than when exercise is performed by fin swimming.

3. Elastic and static respiratory loads which, when applied one at a time, were marginally acceptable were not acceptable when combined, due to CO_2 accumulation and/or dyspnea.

4. Resistive and static respiratory loads which, when applied one at a time, were marginally acceptable were not acceptable when combined, due to CO_2 accumulation and/or dyspnea.

5. While tests according to (3) and (4) caused CO_2 and dyspnea levels to exceed acceptability standards they generally did so only slightly. Hence, it is suggested that designing breathing gear where either elastic and static loads or resistive and static loads are combined, reducing the load limits to 50% of the individually tolerable would provide for acceptable effects of the load combinations.

6. An earlier recommendation from this laboratory that tests of acceptable external respiratory impedance must consider both end-tidal CO_2 levels and dyspnea scores was reaffirmed in this study.

7. Assigning acceptability limits to the Borg-scale for perceived respiratory effort will have to await further study.

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Table I **Ergometer Study**

Respiratory parameters and heart rate

Rest, 1.45 atm abs, 147 kPa, 15 fsw, 4.5 msw

		Elastic load (cm H_2O/L)							
		0		7		14		21	
Parameter	units	mean	SE	mean	SE	mean	SE	mean	SE
$PetCO_2$	mm Hg	39.6	1.4	39.4	0.9	39.2	1.7	38.9	1.5
	kPa	5.27	0.18	5.26	0.12	5.23	0.22	5.18	0.19
dyspnea		–		–		–		–	
br. diff.	Borg	-		-		-		-	
$\dot{V}_E$	$L \cdot min^{-1}$	14.5	1.2	13.9	0.8	15.7	1.4	15.7	1.8
V_t	L	1.09	0.05	0.99	0.11	1.03	0.08	0.85*	0.04
f	min^{-1}	13.7	1.0	14.7	1.6	15.6	1.1	18.9*	2.5
MVV	$L \cdot min^{-1}$	121.4	9.4	107.5*	12.6	112.9	8.3	104.9*	8.0
FEV1%		73	3	74	3	75	3	78	4
VC	L	5.24	0.21	4.59*	0.18	4.32*	0.20	3.98*	0.20
ERV	L	1.77	0.13	1.67	0.04	1.58	0.10	1.42*	0.13
T_i/T_{tot}		0.42	0.02	0.44	0.01	0.43	0.02	0.44	0.02
$\dot{V}O_2$	$L \cdot min^{-1}$	0.44	0.03	0.41	0.02	0.44	0.04	0.42	0.06
WOB/V	$J \cdot L^{-1}$	0.42	0.04	0.57*	0.04	0.87*	0.07	0.80*	0.05
POBin	W	0.19	0.03	0.15	0.02	0.23	0.03	0.21	0.04
POBex	W	0.04	0.01	0.11	0.01	0.20*	0.04	0.17*	0.03
Pm,in	cm H_2O	-4.5	0.2	-5.6	0.8	-9.2*	0.8	-8.7*	0.9
Pm,ex	cm H_2O	1.0	0.5	5.3*	0.6	7.9*	1.1	8.0*	0.6
Pmax,in	cm H_2O	-110.9	15.1	-119.3	16.0	-125.2	10.3	-117.2	6.6
Pmax,ex	cm H_2O	112.1	17.0	109.0	11.4	119.3	10.6	126.1	14.1
HR	min^{-1}	66.6	6.7	65.1	5.0	66.4	4.0	67.1	6.2

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.

Values are averages from all subjects with experiments in duplicate.

An asterisk indicates statistically significant changes from control ($p<0.05$).

Table II **Ergometer Study**

Respiratory parameters and heart rate

Rest, 6.8 atm abs, 690 kPa, 190 fsw, 57 msw

		Elastic load (cm H2O/L)							
		0		7		14		21	
Parameter	units	mean	SE	mean	SE	mean	SE	mean	SE
$PetCO_2$	mm Hg	35.8	1.1	35.7	1.3	35.8	1.5	36.3	1.5
	kPa	4.77	0.15	4.76	0.17	4.77	0.20	4.84	0.20
dyspnea		–		–		–		–	
br. diff.	Borg	-		-		-		-	
$\dot{V}_E$	$L \cdot min^{-1}$	16.5	1.0	16.3	0.9	15.9	0.7	16.8	1.0
V_t	L	1.23	0.08	1.07*	0.07	0.95*	0.03	0.93*	0.05
f	min^{-1}	14.0	1.4	15.7*	1.6	17.0*	1.0	18.5*	1.6
MVV	$L \cdot min^{-1}$	64.4	5.3	63.8	3.7	63.2	4.8	57.0	6.1
FEV1%		53	2	55	3	57	2	57	2
VC	L	5.06	0.16	4.79	0.18	4.29*	0.24	3.87*	0.24
ERV	L	1.67	0.10	1.76	0.08	1.54	0.09	1.42*	0.10
T_i/T_{tot}		0.45	0.02	0.45	0.02	0.45	0.01	0.45	0.01
$\dot{V}O_2$	$L \cdot min^{-1}$	0.50	0.04	0.50	0.03	0.48	0.05	0.48	0.05
WOB/V	$J \cdot L^{-1}$	0.44	0.05	0.54*	0.06	0.72*	0.04	0.96*	0.06
POBin	W	0.23	0.05	0.16	0.04	0.19	0.03	0.28	0.05
POBex	W	0.04	0.01	0.12*	0.01	0.17*	0.02	0.20*	0.02
Pm,in	cm H_2O	-4.5	0.5	-5.6	0.9	-7.2*	1.0	-9.6*	0.6
Pm,ex	cm H_2O	1.2	0.1	5.0*	0.4	5.8*	0.5	8.6*	0.4
Pmax,in	cm H_2O	-112.2	16.1	-114.6	12.7	-127.6	6.5	-121.1	7.7
Pmax,ex	cm H_2O	118.0	18.1	107.8	10.7	126.0	9.2	118.7	16.3
HR	min^{-1}	57.6	4.8	59.5	4.1	61.5	5.7	60.6	4.8

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.

Values are averages from all subjects with experiments in duplicate.

An asterisk indicates statistically significant changes from control ($p<0.05$).

Table III **Ergometer Study**

Respiratory parameters and heart rate

Exercise, 1.45 atm abs, 147 kPa, 15 fsw, 4.5 msw

		Elastic load (cm H2O/L)							
		0		7		14		21	
Parameter	units	mean	SE	mean	SE	mean	SE	mean	SE
$PetCO_2$	mm Hg	42.9	1.2	43.5	1.4	45.6	2.0	41.7	2.7
	kPa	5.72	0.16	5.80	0.18	6.08	0.27	5.56	0.36
dyspnea		0.21	0.12	0.33	0.12	0.60*	0.20	0.69*	0.26
br. diff.	Borg	8.2	0.7	10.1*	0.7	10.9*	0.2	12.4*	0.5
$\dot{V}_E$	$L \cdot min^{-1}$	58.1	5.1	58.2	4.9	61.1	6.2	63.0*	4.5
V_t	L	2.15	0.07	1.97*	0.06	1.88*	0.09	1.73*	0.15
f	min^{-1}	27.2	2.4	29.4	2.2	32.1*	1.9	38.4*	5.3
MVV	$L \cdot min^{-1}$	-		-		-		-	
FEV1%		-		-		-		-	
VC	L	5.37	0.24	4.66*	0.18	4.43*	0.19	4.10*	0.20
ERV	L	1.60	0.03	1.46*	0.04	1.36*	0.05	1.19*	0.09
T_i/T_{tot}		0.50	0.01	0.50	0.01	0.50	0.01	0.50	0.01
$\dot{V}O_2$	$L \cdot min^{-1}$	2.21	0.18	2.34*	0.21	2.33*	0.19	2.37*	0.22
WOB/V	$J \cdot L^{-1}$	0.60	0.07	1.05*	0.02	1.43*	0.07	1.71*	0.17
POBin	W	0.83	0.15	0.83	0.07	1.10*	0.13	1.43*	0.16
POBex	W	0.38	0.11	1.04*	0.14	1.52*	0.28	1.66*	0.32
Pm,in	cm H_2O	-6.1	0.4	-9.3*	0.4	-12.2*	0.7	-16.8*	1.7
Pm,ex	cm H_2O	2.8	0.6	10.7*	0.4	15.7*	1.1	18.1*	1.9
Pmax,in	cm H_2O	-112.9	10.4	-127.1	7.4	-124.0	8.9	-115.0	6.6
Pmax,ex	cm H_2O	114.2	12.3	112.1	10.7	108.6	9.0	106.7	12.7
HR	min^{-1}	126.5	4.9	130.0	4.5	131.6*	2.9	134.1*	4.5

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.
Values are averages from all subjects with experiments in duplicate.
An asterisk indicates statistically significant changes from control ($p<0.05$).

Table IV **Ergometer Study**

Respiratory parameters and heart rate

Exercise, 6.8 atm abs, 690 kPa, 190 fsw, 57 msw

		Elastic load (cm H2O/L)							
		0		7		14		21	
Parameter	units	mean	SE	mean	SE	mean	SE	mean	SE
$PetCO_2$	mm Hg	49.2	1.5	50.1	2.2	51.2*	2.0	50.5*	3.6
	kPa	6.57	0.20	6.68	0.29	6.82*	0.27	6.73*	0.48
dyspnea		0.04	0.04	0.40*	0.14	0.31*	0.12	0.85*	0.30
br. diff.	Borg	8.4	0.7	9.9*	0.8	11.2*	0.9	13.3*	0.7
$\dot{V}_E$	$L \cdot min^{-1}$	49.9	3.9	51.4	3.8	50.7	4.2	51.6	3.9
V_t	L	1.92	0.07	1.80*	0.05	1.69*	0.07	1.60*	0.06
f	min^{-1}	26.2	2.2	28.7*	2.0	30.1*	2.3	32.3*	2.1
MVV	$L \cdot min^{-1}$	–		–		–		–	
FEV1%		–		–		–		–	
VC	L	5.27	0.19	4.78*	0.18	4.26*	0.21	3.84*	0.20
ERV	L	1.91	0.09	1.69*	0.14	1.39*	0.14	1.19*	0.11
T_i/T_{tot}		0.52	0.01	0.51*	0.01	0.50*	0.01	0.50*	0.01
$\dot{V}O_2$	$L \cdot min^{-1}$	2.19	0.20	2.12	0.20	2.19	0.19	2.29	0.22
WOB/V	$J \cdot L^{-1}$	0.78	0.09	0.97*	0.07	1.34*	0.08	1.88*	0.09
POBin	W	0.97	0.20	0.94	0.23	1.12	0.17	1.47*	0.23
POBex	W	0.43	0.09	0.78*	0.05	1.10*	0.14	1.50*	0.16
Pm,in	cm H_2O	-7.3	0.9	-9.7*	1.0	-12.8*	0.9	-17.3*	1.3
Pm,ex	cm H_2O	5.1	0.9	8.3*	0.2	12.7*	0.7	18.1*	0.7
Pmax,in	cm H_2O	-118.6	7.6	-124.3	7.0	-120.2	3.0	-117.6	5.4
Pmax,ex	cm H_2O	119.2	9.3	110.0	9.8	103.9	8.5	101.1	12.1
HR	min^{-1}	115.2	4.4	117.6	3.9	120.9*	4.3	122.8*	5.2

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.

Values are averages from all subjects with experiments in duplicate.

An asterisk indicates statistically significant changes from control ($p<0.05$).

Table V **Fin Study**

Respiratory parameters and heart rate

Rest, 1.45 atm abs, 147 kPa, 15 fsw, 4.5 msw

		Elastic load (cm H_2O/L)							
		0		7		14		21	
Parameter	units	mean	SE	mean	SE	mean	SE	mean	SE
PetCO2	mm Hg	41.6	1.9	41.9	1.4	42.0	1.2	41.2	1.2
	kPa	5.55	0.25	5.58	0.19	5.60	0.16	5.50	0.16
dyspnea		-		-		-		-	
br. diff.	Borg	-		-		-		-	
$\dot{V}_E$	$L \cdot min^{-1}$	13.6	0.8	13.2	0.9	14.5	1.3	14.8	0.7
V_t	L	1.27	0.16	1.06*	0.08	0.98*	0.09	0.92*	0.08
f	min^{-1}	11.1	1.0	12.6	0.8	14.9*	0.6	16.5*	1.0
MVV	$L \cdot min^{-1}$	121.1	12.8	117.0	5.9	123.1	11.0	117.3	10.8
FEV1%		70	4	73*	4	76*	3	78*	3
VC	L	5.31	0.27	4.63*	0.14	4.32*	0.22	3.86*	0.31
ERV	L	1.68	0.05	1.72	0.07	1.67	0.09	1.50	0.13
T_i/T_{tot}		0.40	0.01	0.41	0.01	0.40	0.01	0.43	0.01
$\dot{V}O_2$	$L \cdot min^{-1}$	0.43	0.03	0.39	0.04	0.43	0.03	0.43	0.05
WOB/V	$J \cdot L^{-1}$	0.30	0.01	0.51*	0.03	0.70	0.06	0.92*	0.08
POBin	W	0.14	0.01	0.13	0.02	0.16	0.03	0.25*	0.04
POBex	W	0.01	0.00	0.10*	0.02	0.13*	0.03	0.19*	0.02
Pm,in	cm H_2O	-3.4	0.2	-5.6*	0.4	-7.4*	0.7	-9.4*	0.9
Pm,ex	cm H_2O	0.6	0.1	5.3*	0.7	7.3*	0.8	9.0*	1.0
Pmax,in	cm H_2O	-92.8	10.6	-91.8	13.2	-88.0	18.9	-89.9	14.6
Pmax,ex	cm H_2O	94.8	14.4	101.1	13.1	101.1	17.3	100.9	14.8
HR	min^{-1}	65.0	7.8	64.5	5.9	68.9	7.4	66.9	4.8

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.

Values are averages from all subjects with experiments in duplicate.

An asterisk indicates statistically significant changes from control ($p<0.05$).

Table VI **Fin Study**

Respiratory parameters and heart rate

Rest, 6.8 atm abs, 690 kPa, 190 fsw, 57 msw

		Elastic load (cm H_2O/L)							
		0		7		14		21	
Parameter	units	mean	SE	mean	SE	mean	SE	mean	SE
PetCO2	mm Hg	36.9	2.0	36.0	1.3	37.0	1.7	37.6	1.9
	kPa	4.92	0.27	4.80	0.18	4.93	0.23	5.01	0.25
dyspnea		-		-		-		-	
br. diff.	Borg	-		-		-		-	
$\dot{V}_E$	$L \cdot min^{-1}$	16.5	0.4	17.0	0.2	17.4	0.9	16.2	0.1
V_t	L	1.24	0.15	1.21	0.11	1.11	0.08	1.02*	0.09
f	min^{-1}	14.0	1.4	14.5	1.2	16.0*	1.4	16.4*	1.3
MVV	$L \cdot min^{-1}$	64.4	7.5	65.3	6.8	61.2	4.8	66.0	8.2
FEV1%		50	3	52	4	50	3	58*	3
VC	L	5.15	0.23	4.71*	0.19	4.23*	0.22	3.82*	0.36
ERV	L	1.61	0.05	1.68	0.03	1.47	0.16	1.39	0.20
T_i/T_{tot}		0.43	0.01	0.42	0.00	0.44	0.01	0.43	0.01
$\dot{V}O_2$	$L \cdot min^{-1}$	0.40	0.05	0.39	0.02	0.44	0.03	0.40	0.02
WOB/V	$J \cdot L^{-1}$	0.39	0.05	0.56*	0.06	0.85*	0.05	1.05*	0.10
POBin	W	0.20	0.02	0.17	0.03	0.26	0.01	0.29*	0.03
POBex	W	0.03	0.01	0.16*	0.02	0.20*	0.02	0.23*	0.02
Pm,in	cm H_2O	-4.2	0.4	-5.5*	0.4	-8.0*	0.6	-10.6*	0.9
Pm,ex	cm H_2O	0.6	0.3	5.7*	0.8	8.2*	0.7	10.4*	1.1
Pmax,in	cm H_2O	-103.0	8.0	-103.3	17.1	-91.1	3.8	-113.7	7.6
Pmax,ex	cm H_2O	109.5	15.3	104.1	7.9	116.0	11.7	111.3	9.5
HR	min^{-1}	57.5	5.8	57.7	4.9	60.4	4.1	57.2	5.6

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.

Values are averages from all subjects with experiments in duplicate.

An asterisk indicates statistically significant changes from control ($p<0.05$).

Table VII **Fin Study**

Respiratory parameters and heart rate

Exercise, 1.45 atm abs, 147 kPa, 15 fsw, 4.5 msw

		Elastic load (cm H_2O/L)							
		0		7		14		21	
Parameter	units	mean	SE	mean	SE	mean	SE	mean	SE
PetCO2	mm Hg	44.6	2.1	44.7	2.1	46.9*	1.7	46.7*	2.3
	kPa	5.94	0.28	5.96	0.28	6.26	0.22	6.23	0.30
dyspnea		0.26	0.19	0.40	0.19	0.26	0.19	0.32	0.20
br. diff.	Borg	10.1	1.0	10.5	1.2	10.8	0.9	12.1*	1.1
$\dot{V}_E$	$L \cdot min^{-1}$	45.8	3.4	48.3	5.1	46.4	3.6	48.6	4.6
V_t	L	2.46	0.18	1.98*	0.09	1.90*	0.14	1.78*	0.09
f	min^{-1}	19.1	1.9	24.6*	3.1	24.8*	2.3	27.9*	3.5
MVV	$L \cdot min^{-1}$	-		-		-		-	
FEV1%		-		-		-		-	
VC	L	5.54	0.34	4.84*	0.23	4.37*	0.26	4.10*	0.34
ERV	L	1.57	0.06	1.59	0.05	1.42*	0.10	1.28*	0.15
T_i/T_{tot}		0.47	0.01	0.46	0.01	0.46	0.01	0.46	0.01
$\dot{V}O_2$	$L \cdot min^{-1}$	1.83	0.16	1.85	0.15	1.88	0.15	1.84	0.12
WOB/V	$J \cdot L^{-1}$	0.40	0.01	0.97*	0.05	1.39*	0.13	1.67*	0.08
POBin	W	0.53	0.04	0.71*	0.06	0.92*	0.06	1.16*	0.08
POBex	W	0.12	0.03	0.80*	0.11	1.05*	0.18	1.26*	0.13
Pm,in	cm H_2O	-4.2	0.2	-8.9*	0.5	-12.8*	0.7	-16.9*	1.1
Pm,ex	cm H_2O	1.5	0.3	10.3*	0.6	14.8*	1.7	18.2*	1.1
Pmax,in	cm H_2O	-101.9	9.3	-104.3	14.3	-103.3	13.7	-106.7	12.2
Pmax,ex	cm H_2O	100.4	10.9	97.4	8.8	100.0	10.0	90.1	10.0
HR	min^{-1}	122.2	5.7	123.9	5.0	125.3	6.2	128.3*	2.0

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.

Values are averages from all subjects with experiments in duplicate.

An asterisk indicates statistically significant changes from control ($p<0.05$).

Table VIII **Fin Study**

Respiratory parameters and heart rate

Exercise, 6.8 atm abs, 690 kPa, 190 fsw, 57 msw

		Elastic load (cm H_2O/L) 0		7		14		21	
Parameter	units	mean	SE	mean	SE	mean	SE	mean	SE
PetCO2	mm Hg	48.4	2.4	47.1*	1.9	51.4*	2.2	51.5*	2.4
	kPa	6.46	0.32	6.28	0.26	6.86	0.30	6.87	0.32
dyspnea		0.32	0.21	0.32	0.21	0.34	0.21	0.34	0.21
br. diff.	Borg	10.3	1.2	10.4	1.1	11.2*	1.3	11.8*	1.1
$\dot{V}_E$	$L \cdot min^{-1}$	45.0	4.1	43.5	3.8	43.6	3.5	44.6	3.0
V_t	L	2.08	0.17	1.92*	0.13	1.83*	0.11	1.76*	0.15
f	min^{-1}	22.2	2.8	22.8	2.2	24.3*	2.7	25.5*	2.9
MVV	$L \cdot min^{-1}$	-		-		-		-	
FEV1%		-		-		-		-	
VC	L	5.35	0.29	4.77*	0.31	4.28*	0.24	3.88*	0.34
ERV	L	1.76	0.07	1.60*	0.14	1.37*	0.16	1.21*	0.19
T_i/T_{tot}		0.49	0.01	0.48*	0.01	0.47*	0.01	0.48*	0.01
$\dot{V}O_2$	$L \cdot min^{-1}$	1.85	0.20	1.77	0.19	1.89	0.12	2.00*	0.12
WOB/V	$J \cdot L^{-1}$	0.66	0.06	0.81*	0.09	1.29*	0.05	1.84*	0.13
POBin	W	0.79	0.10	0.63*	0.11	0.91*	0.09	1.16*	0.08
POBex	W	0.29	0.06	0.56*	0.09	0.88*	0.10	1.25*	0.09
Pm,in	cm H_2O	-6.7	0.5	-7.8*	0.8	-12.5*	0.9	-17.1*	1.5
Pm,ex	cm H_2O	3.9	0.6	7.6*	0.9	12.8*	0.5	18.5*	1.6
Pmax,in	cm H_2O	-110.1	5.9	-112.5	2.0	-107.5	9.9	-112.8	9.4
Pmax,ex	cm H_2O	106.8	5.6	96.4	6.4	104.3	7.0	98.0	7.0
HR	min^{-1}	114.8	5.0	110.7	6.3	119.1	4.4	110.6	10.8

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.

Values are averages from all subjects with experiments in duplicate.

An asterisk indicates statistically significant changes from control ($p<0.05$).

Table IX **RES Study**

Respiratory parameters and heart rate

Rest, 1.45 atm abs, 147 kPa, 15 fsw, 4.5 msw

		Load combination					
		control		ES		RS	
Parameter	units	mean	SE	mean	SE	mean	SE
PetCO2	mm Hg	41.6	1.8	40.7	2.1	39.4*	1.9
	kPa	5.55	0.24	5.43	0.28	5.25*	0.25
dyspnea		-		-		-	
br. diff.	Borg	-		-		-	
$\dot{V}_E$	$L \cdot min^{-1}$	13.6	0.6	13.7	0.9	14.6	0.8
V_t	L	1.27	0.12	1.06*	0.05	1.32	0.16
f	min^{-1}	11.1	1.0	13.1*	1.2	11.7	1.4
MVV	$L \cdot min^{-1}$	109.0	12.3	100.3	8.5	89.4*	8.0
FEV1%		71	4	72	5	70	4
VC	L	5.24	0.36	4.50*	0.29	5.16	0.26
ERV	L	1.45	0.12	1.09*	0.07	1.17*	0.09
T_i/T_{tot}		0.41	0.01	0.39	0.02	0.43	0.01
$\dot{V}O_2$	$L \cdot min^{-1}$	0.43	0.03	0.45	0.02	0.41	0.03
WOB/V	$J \cdot L^{-1}$	0.34	0.02	0.57	0.04	0.35	0.08
POBin	W	0.16	0.02	0.16	0.03	0.14	0.03
POBex	W	0.01	0.01	0.11*	0.01	0.05	0.03
Pm,in	cm H_2O	-3.9	0.3	-5.6*	0.5	-4.0	0.3
Pm,ex	cm H_2O	0.5	0.4	5.5*	0.3	1.8	0.6
Pmax,in	cm H_2O	-95.2	14.9	-100.1	13.6	-91.5	16.4
Pmax,ex	cm H_2O	91.6	9.9	108.8	10.4	105.9	10.3
HR	min^{-1}	68.6	3.1	67.8	1.4	65.2	2.8

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.
Values are averages from all subjects with experiments in duplicate.
An asterisk indicates statistically significant changes from control ($p<0.05$).

Table X

RES Study

Respiratory parameters and heart rate

Rest, 6.8 atm abs, 690 kPa, 190 fsw, 57 msw

		Load combination					
		control		ES		RS	
Parameter	units	mean	SE	mean	SE	mean	SE
PetCO2	mm Hg	37.4	1.5	37.6	2.2	36.7	1.9
	kPa	4.99	0.20	5.02	0.30	4.90	0.26
dyspnea		-		-		-	
br. diff.	Borg	-		-		-	
$\dot{V}_E$	$L \cdot min^{-1}$	17.7	1.7	18.4	1.8	17.8	1.4
V_t	L	1.37	0.17	1.20*	0.10	1.31	0.11
f	min^{-1}	13.6	1.6	15.6*	1.7	14.2	1.8
MVV	$L \cdot min^{-1}$	62.0	3.7	58.4	5.1	58.6	5.8
FEV1%		50	4	50	4	49	4
VC	L	5.25	0.41	4.70*	0.41	5.20	0.32
ERV	L	1.57	0.22	1.18*	0.16	1.27*	0.14
T_i/T_{tot}		0.44	0.02	0.44	0.01	0.44	0.02
$\dot{V}O_2$	$L \cdot min^{-1}$	0.44	0.03	0.45	0.03	0.42	0.02
WOB/V	$J \cdot L^{-1}$	0.38	0.02	0.44	0.04	0.46	0.03
POBin	W	0.20	0.02	0.12*	0.02	0.24	0.02
POBex	W	0.05	0.01	0.14*	0.03	0.06	0.01
Pm,in	cm H_2O	-3.6	0.2	-3.6	0.6	-4.4	0.3
Pm,ex	cm H_2O	1.6	0.2	5.6*	0.4	1.6	0.3
Pmax,in	cm H_2O	-131.8	9.7	-119.1	14.5	-122.8	10.3
Pmax,ex	cm H_2O	111.6	13.7	115.5	11.3	117.5	9.1
HR	min^{-1}	63.9	3.5	66.5	3.9	64.3	2.8

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.

Values are averages from all subjects with experiments in duplicate.

An asterisk indicates statistically significant changes from control ($p<0.05$).

Table XI **RES Study**

Respiratory parameters and heart rate

Exercise, 1.45 atm abs, 147 kPa, 15 fsw, 4.5 msw

		Load combination					
		control		ES		RS	
Parameter	units	mean	SE	mean	SE	mean	SE
PetCO2	mm Hg	44.1	1.9	46.0*	2.4	44.6	2.2
	kPa	5.88	0.25	6.14*	0.32	5.95	0.30
dyspnea		0.48	0.21	0.48	0.21	0.48	0.20
br. diff.	Borg	8.6	1.2	10.5*	1.1	10.7*	0.9
$\dot{V}_E$	$L \cdot min^{-1}$	55.2	3.2	53.7	2.7	55.7	2.7
V_t	L	2.26	0.18	2.12*	0.08	2.44*	0.21
f	min^{-1}	25.0	2.4	25.8	2.1	23.8*	2.7
MVV	$L \cdot min^{-1}$	-		-		-	
FEV1%		-		-		-	
VC	L	5.45	0.43	4.83*	0.34	5.48	0.31
ERV	L	1.51	0.14	1.12*	0.11	1.24*	0.08
T_i/T_{tot}		0.48	0.01	0.47*	0.01	0.50*	0.01
$\dot{V}O_2$	$L \cdot min^{-1}$	2.24	0.16	2.27	0.11	2.27	0.11
WOB/V	$J \cdot L^{-1}$	0.49	0.03	1.02*	0.05	1.52*	0.09
POBin	W	0.78	0.12	0.80	0.03	1.54*	0.11
POBex	W	0.22	0.03	0.98*	0.07	1.50*	0.16
Pm,in	cm H_2O	-5.3	0.6	-9.2*	0.5	-10.0*	0.7
Pm,ex	cm H_2O	2.2	0.4	11.4*	0.8	10.4*	0.9
Pmax,in	cm H_2O	-106.0	10.6	-114.2	15.7	-113.1	14.6
Pmax,ex	cm H_2O	99.7	8.7	105.9	11.1	108.7	6.3
HR	min^{-1}	134.3	2.6	136.4	2.5	136.1	2.6

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.
Values are averages from all subjects with experiments in duplicate.
An asterisk indicates statistically significant changes from control ($p<0.05$).

Table XII **RES Study**

Respiratory parameters and heart rate

Exercise, 6.8 atm abs, 690 kPa, 190 fsw, 57 msw

		Load combination					
		control		ES		RS	
Parameter	units	mean	SE	mean	SE	mean	SE
PetCO2	mm Hg	50.6	2.1	54.2*	2.9	52.3*	2.2
	kPa	6.75	0.28	7.22*	0.39	6.97*	0.29
dyspnea		0.38	0.23	0.48*	0.22	0.56*	0.23
br. diff.	Borg	9.1	1.2	11.1*	1.3	10.1*	1.1
$\dot{V}_E$	$L \cdot min^{-1}$	46.0	2.1	43.2*	3.0	42.9*	1.7
V_t	L	2.20	0.20	2.08*	0.24	2.15	0.20
f	min^{-1}	21.6	2.0	22.2	3.0	20.8	2.4
MVV	$L \cdot min^{-1}$	-		-		-	
FEV1%		-		-		-	
VC	L	5.26	0.38	4.54*	0.38	5.14*	0.32
ERV	L	1.66	0.10	1.22*	0.15	1.34*	0.10
T_i/T_{tot}		0.49	0.02	0.46*	0.02	0.51*	0.02
$\dot{V}O_2$	$L \cdot min^{-1}$	2.25	0.15	2.15	0.11	2.10*	0.12
WOB/V	$J \cdot L^{-1}$	0.64	0.03	0.75*	0.08	1.19*	0.08
POBin	W	0.76	0.09	0.56	0.05	1.03	0.10
POBex	W	0.31	0.01	0.56*	0.09	0.85*	0.17
Pm,in	cm H_2O	-5.9	0.3	-7.2*	1.1	-8.7*	0.6
Pm,ex	cm H_2O	4.2	0.5	8.1*	0.8	7.2*	0.7
Pmax,in	cm H_2O	-124.4	9.2	-118.6	10.5	-123.4	13.9
Pmax,ex	cm H_2O	110.4	8.5	106.6	7.7	112.0	5.7
HR	min^{-1}	124.4	1.8	127.0	2.8	123.5	1.7

Volumes are given in BTPS except $\dot{V}O_2$ which is in STPD.
Values are averages from all subjects with experiments in duplicate.
An asterisk indicates statistically significant changes from control ($p<0.05$).

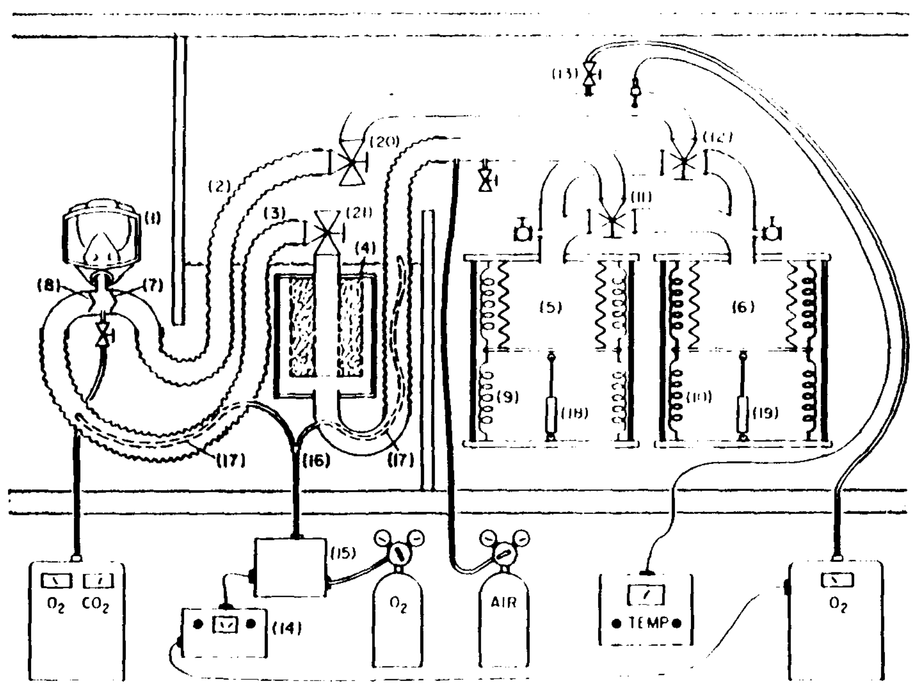


Fig 1 Schematic of the closed-circuit breathing apparatus, for parts and their functions, see text.

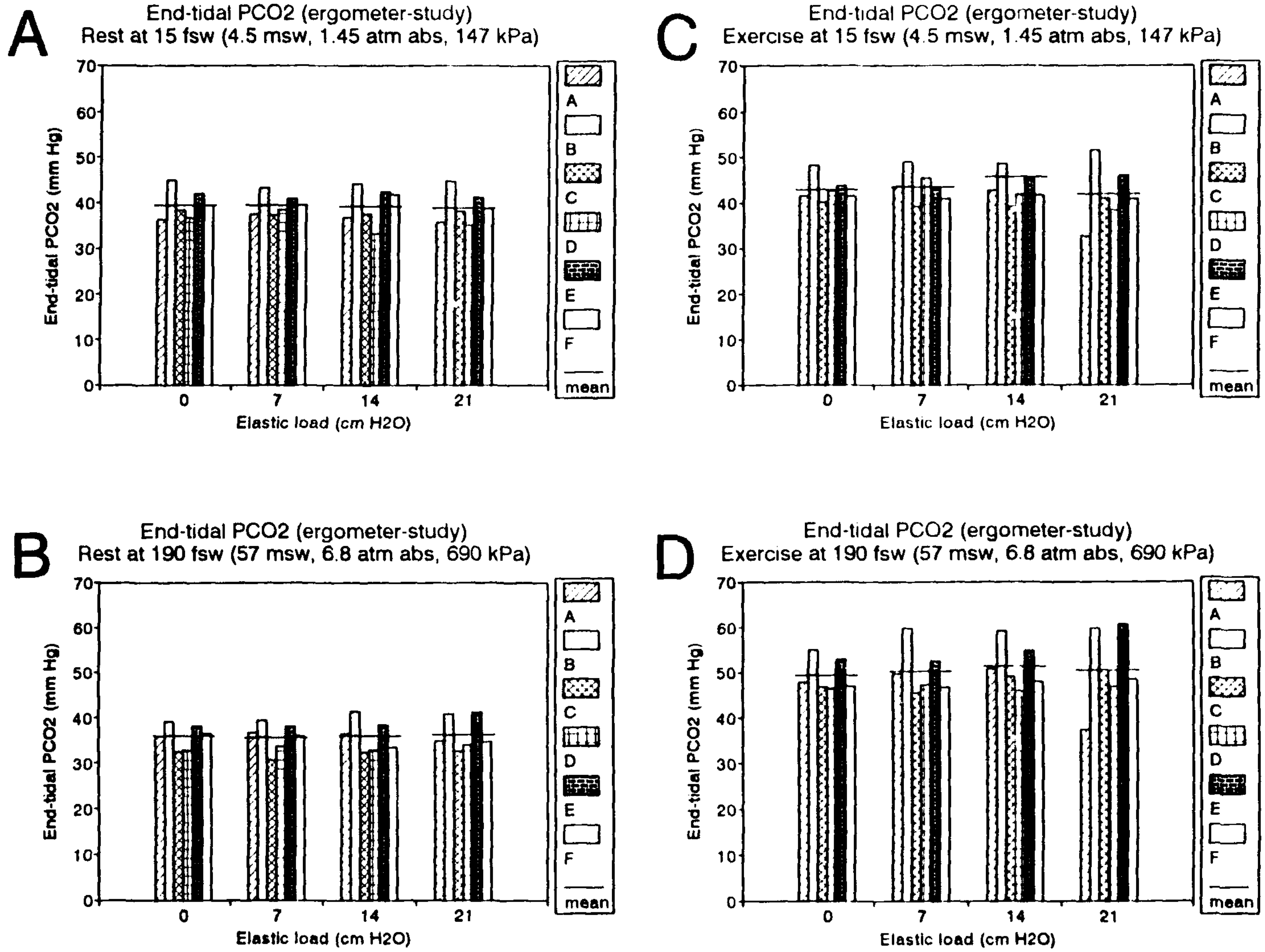


Fig 2 End-tidal CO_2 plotted for the different elastic loads during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

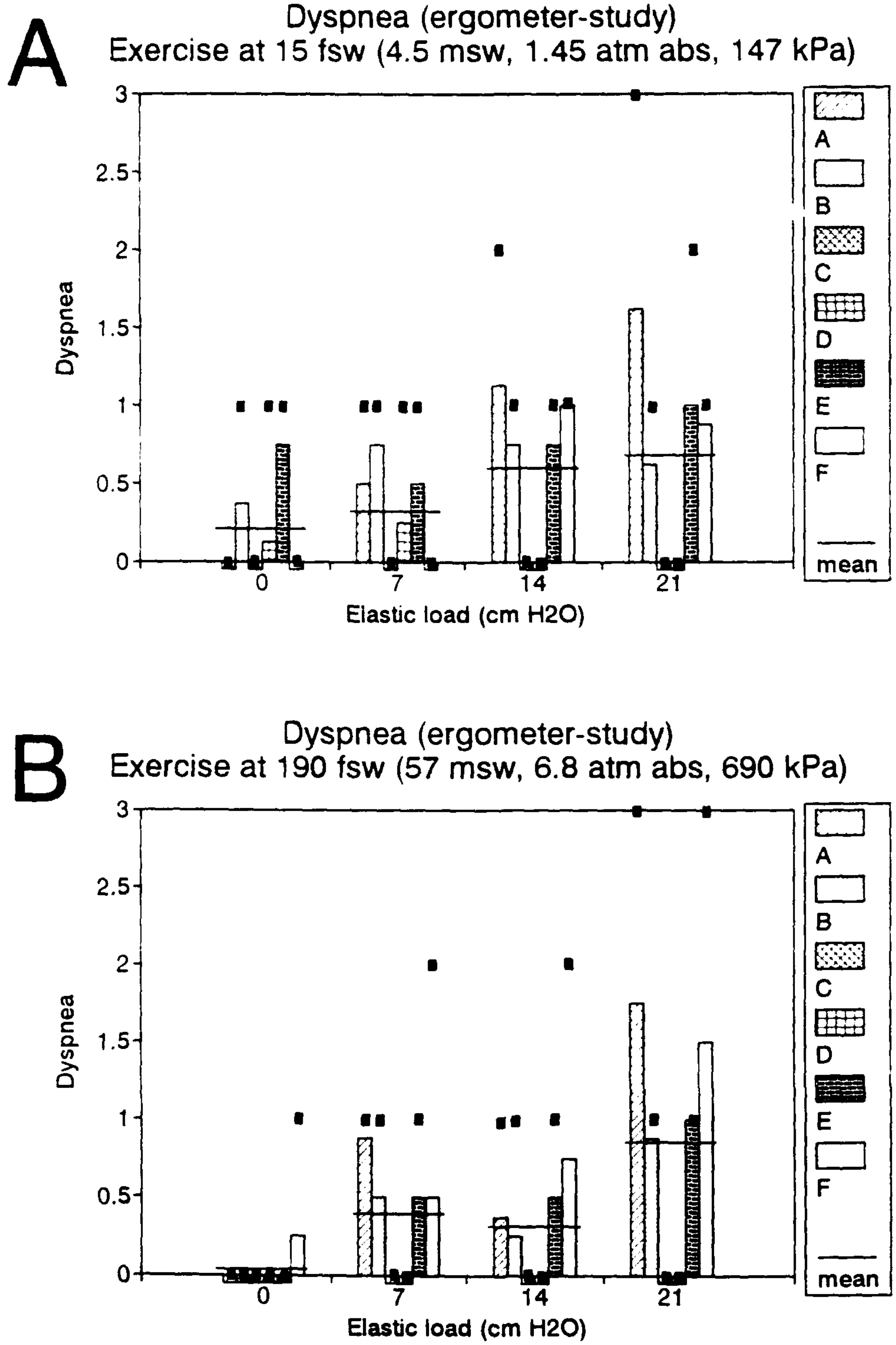
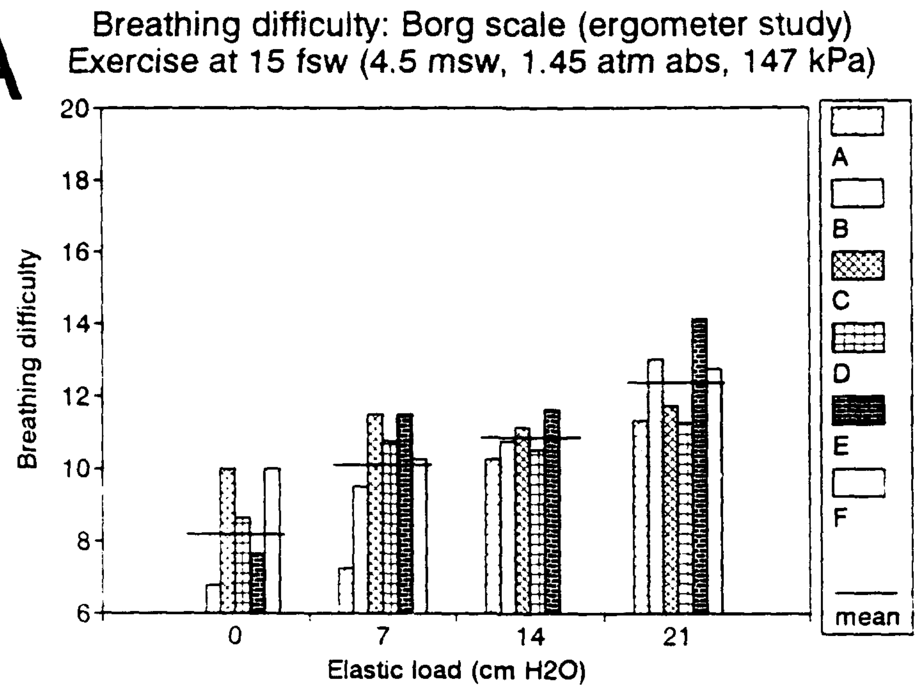


Fig 3 Dyspnea scores plotted for the different elastic loads during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean, dots indicate the highest score reported by each subject. Panel A: data from exercise at the shallow depth, panel B: exercise at the greater depth.

A



B

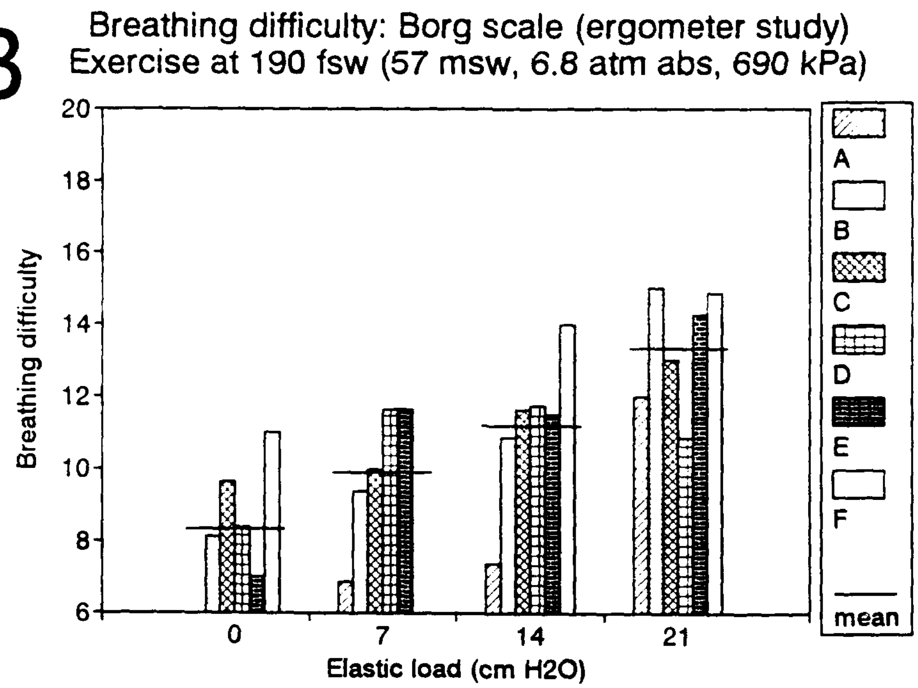


Fig 4 Breathing difficulty (Borg-scale) plotted for the different elastic loads during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from exercise at the shallow depth, panel B: exercise at the greater depth.

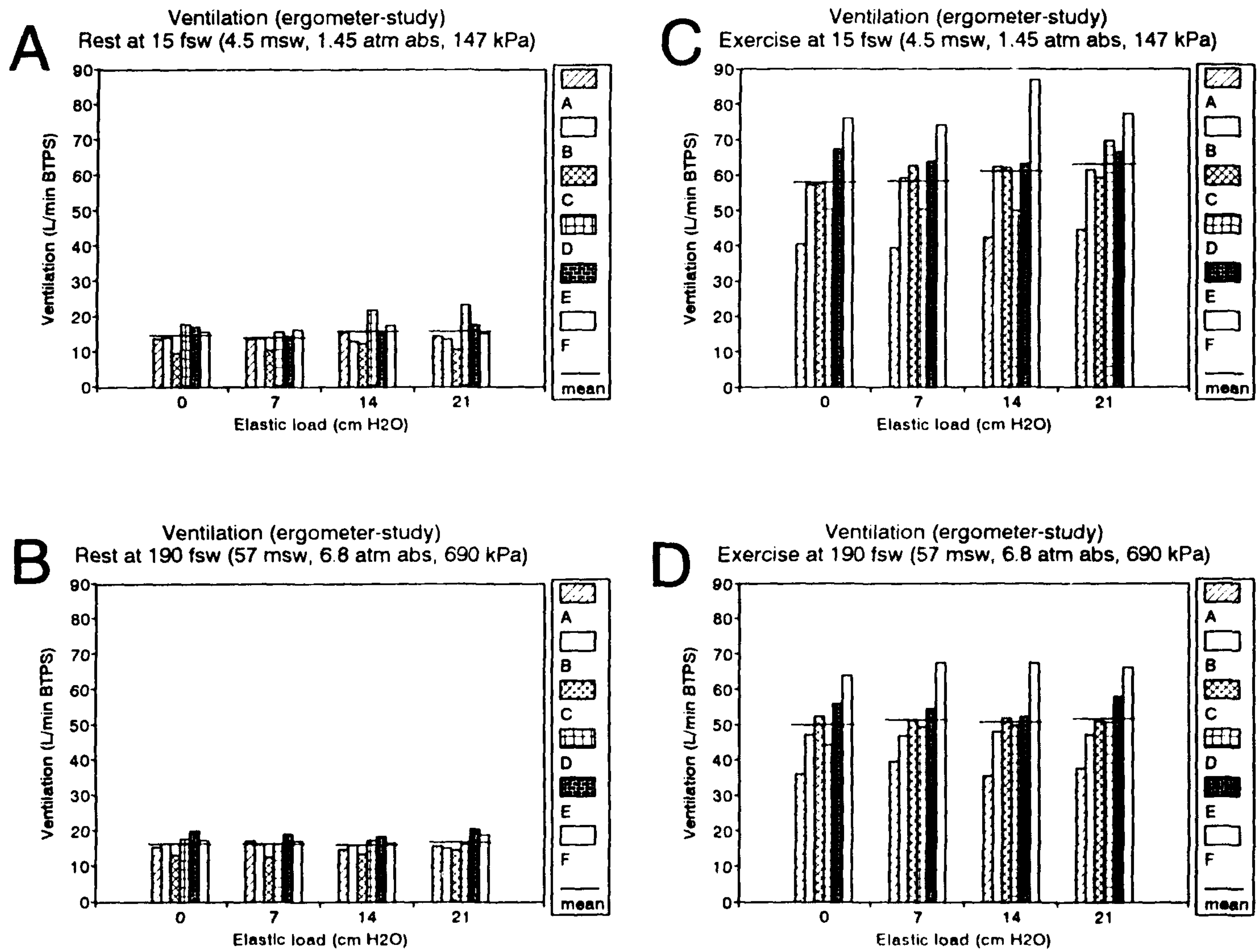


Fig 5 Ventilation ($\dot{V}_E$) plotted for the different elastic loads during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

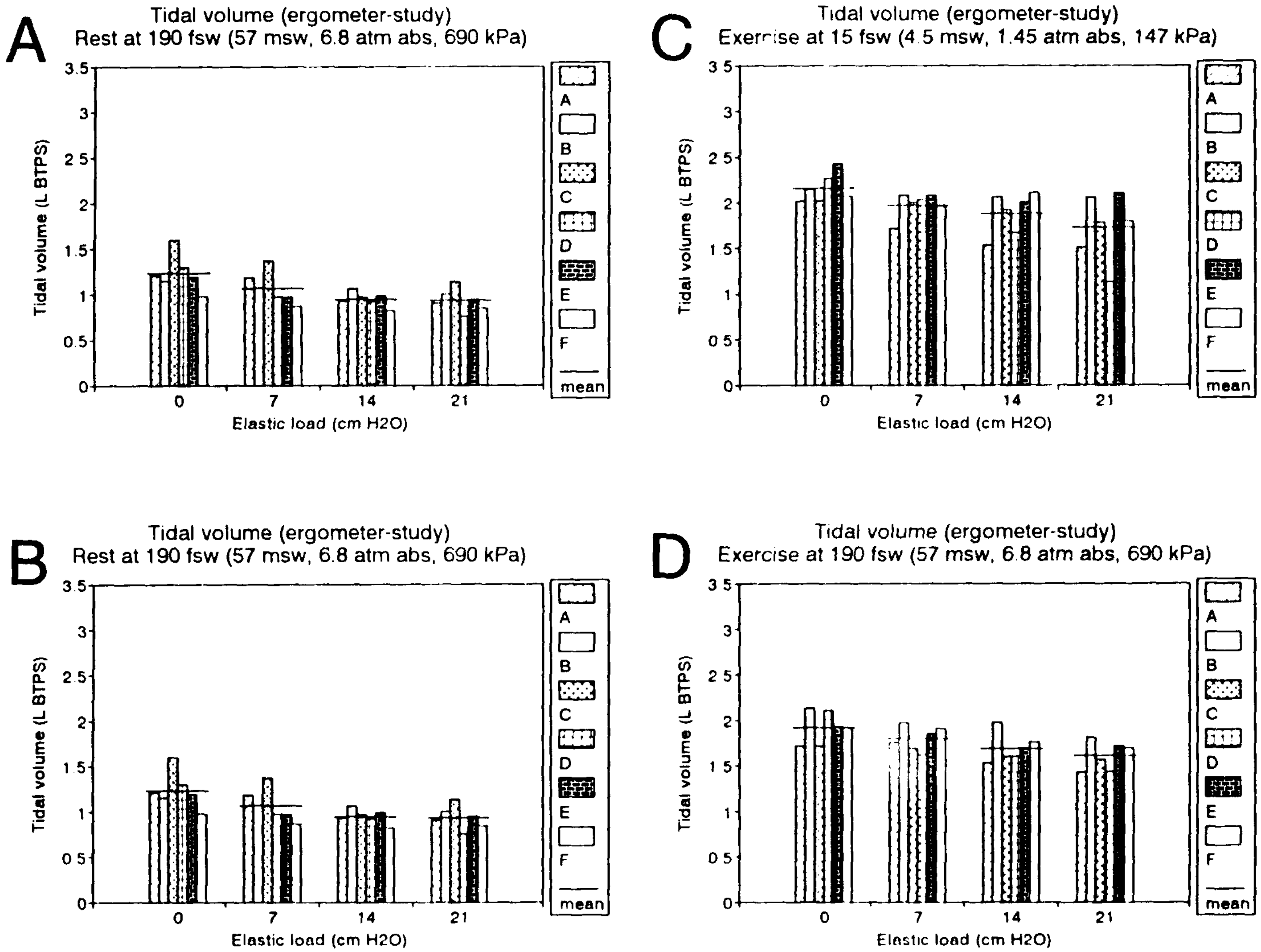


Fig 6 Tidal volume plotted for the different elastic loads during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

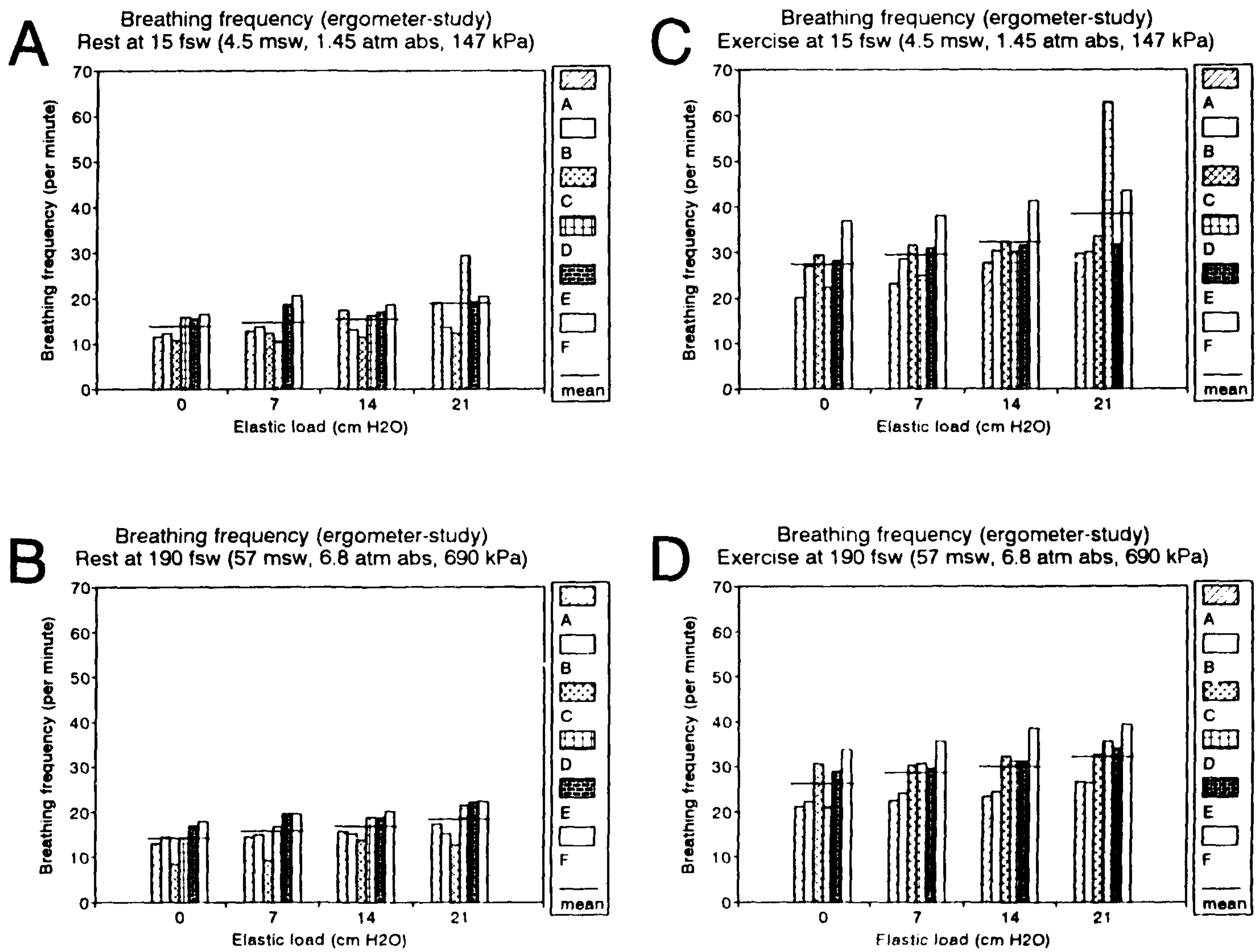


Fig 7 Breathing frequency plotted for the different elastic loads during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

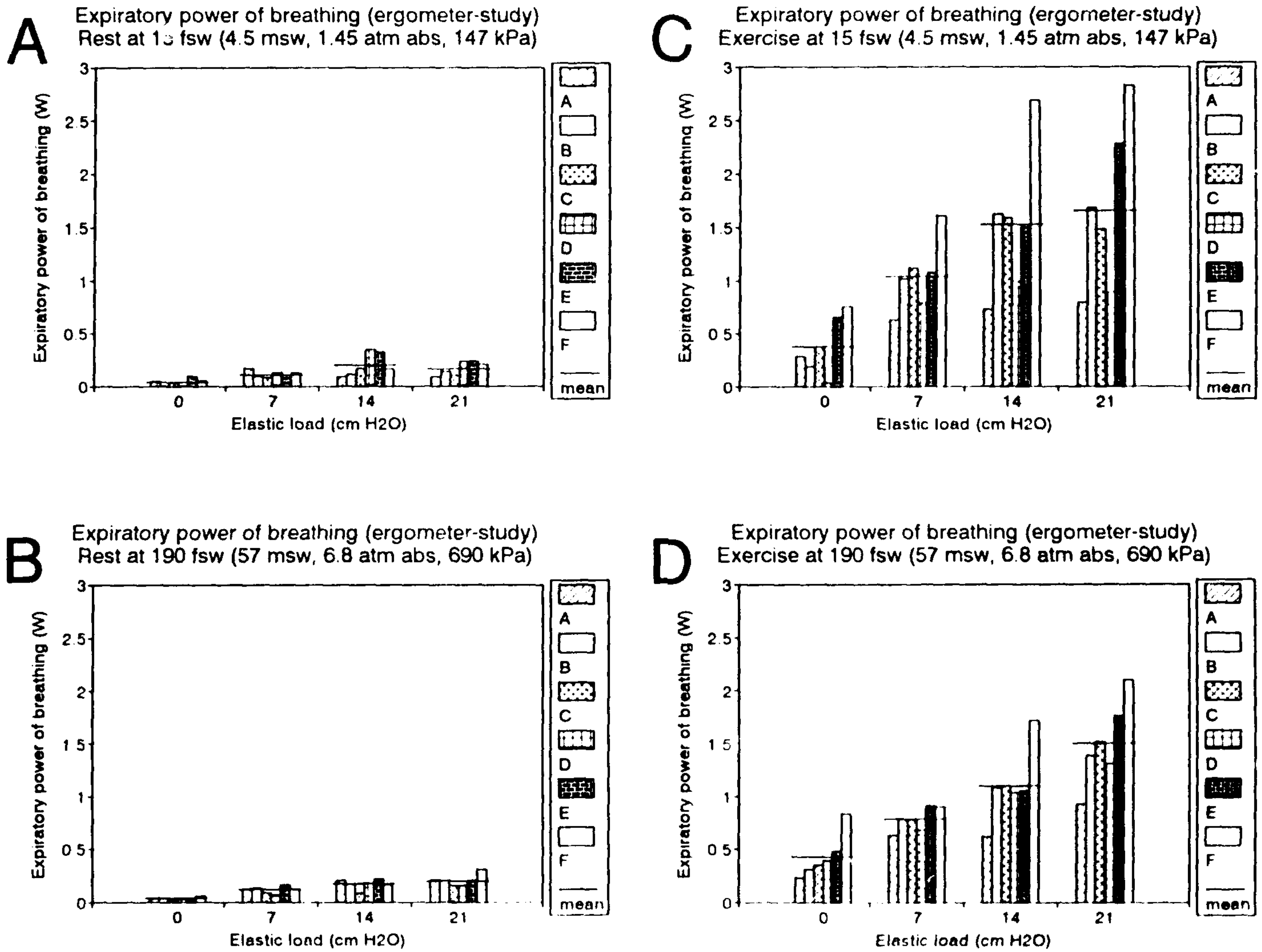


Fig 8 Expiratory power of breathing plotted for the different elastic loads during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shal' w depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

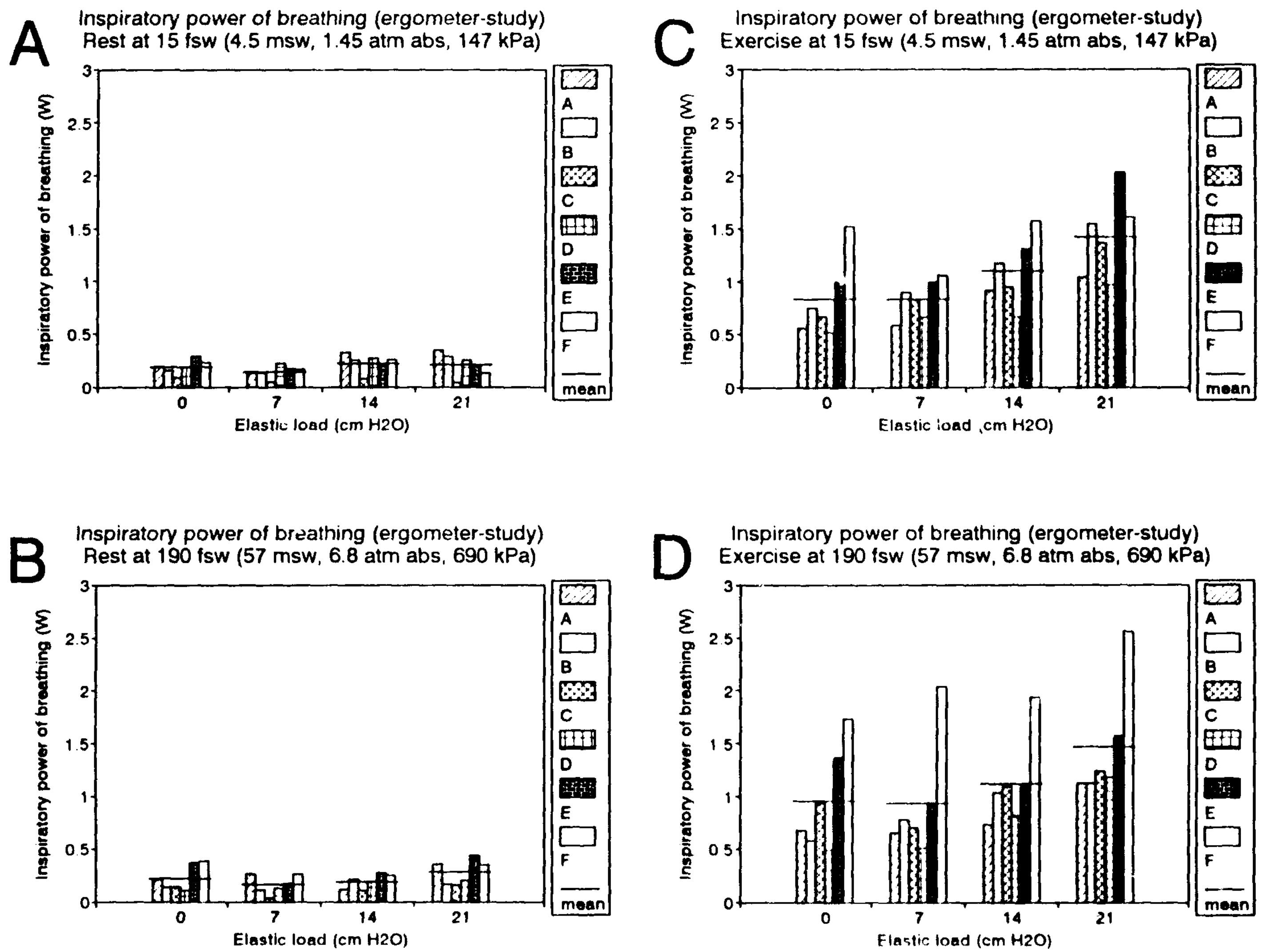


Fig 9 Inspiratory power of breathing plotted for the different elastic loads during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

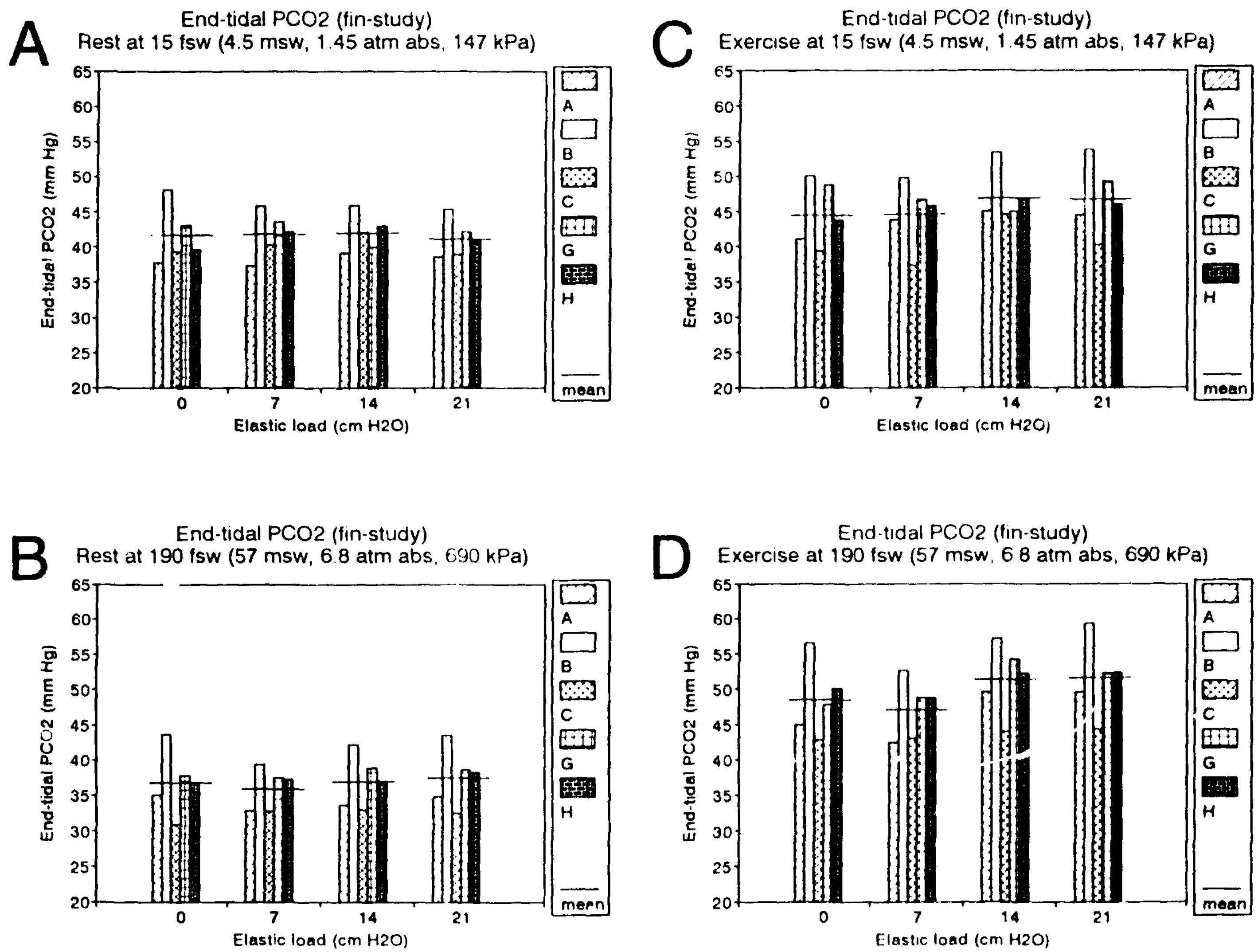


Fig 10 End-tidal CO_2 plotted for the different elastic loads during fin swimming. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

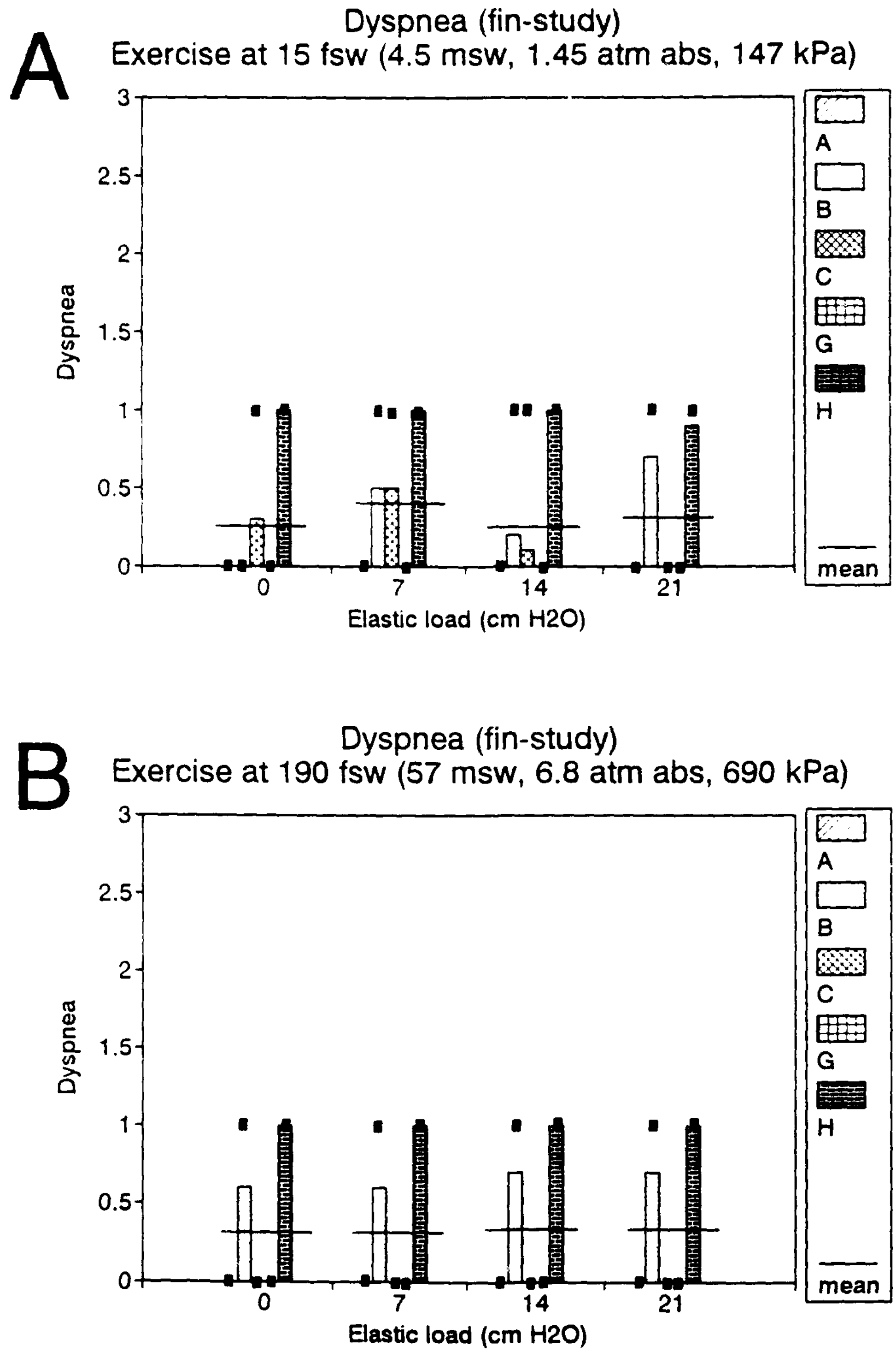
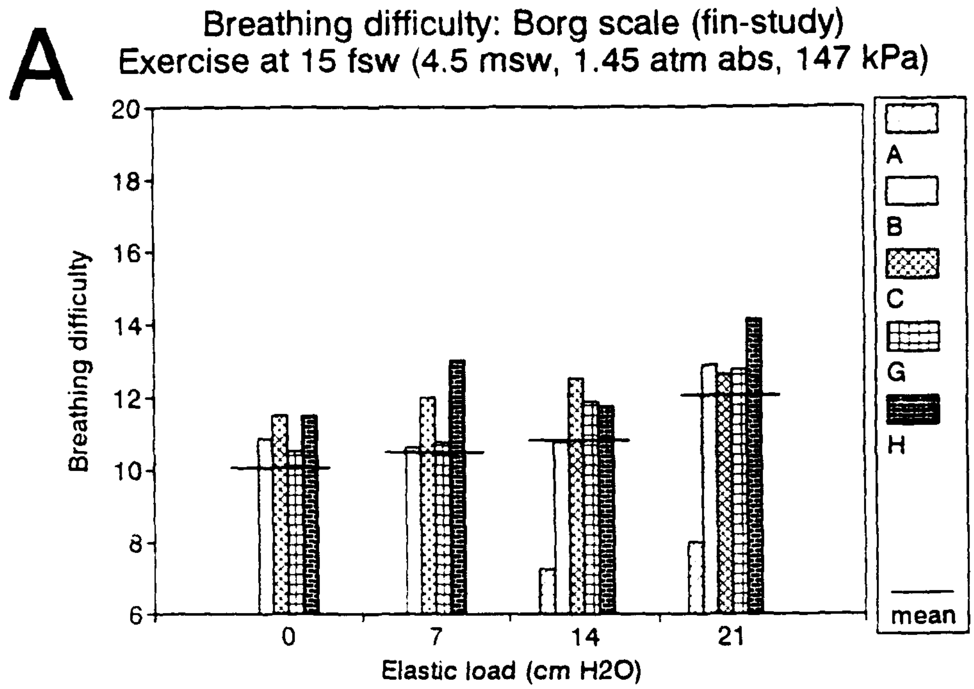


Fig 11 Dyspnea scores plotted for the different elastic loads during fin swimming. Each bar represents one subject, the horizontal line shows the group mean, dots indicate the highest score reported by each subject. Panel A: data from exercise at the shallow depth, panel B: exercise at the greater depth.



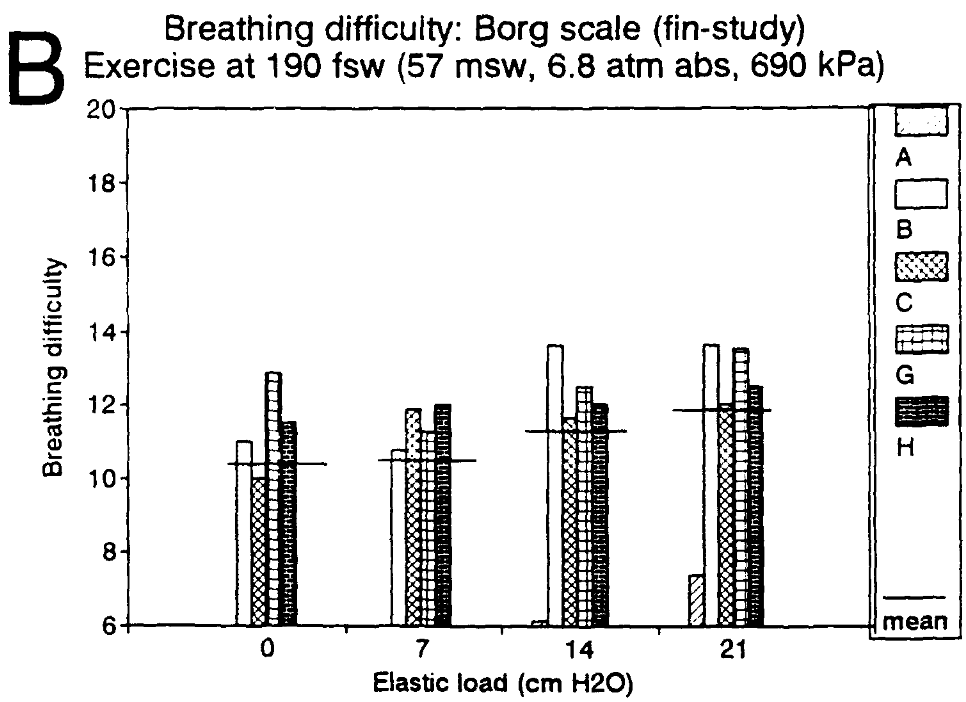


Fig 12 Breathing difficulty (Borg-scale) plotted for the different elastic loads during fin swimming. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

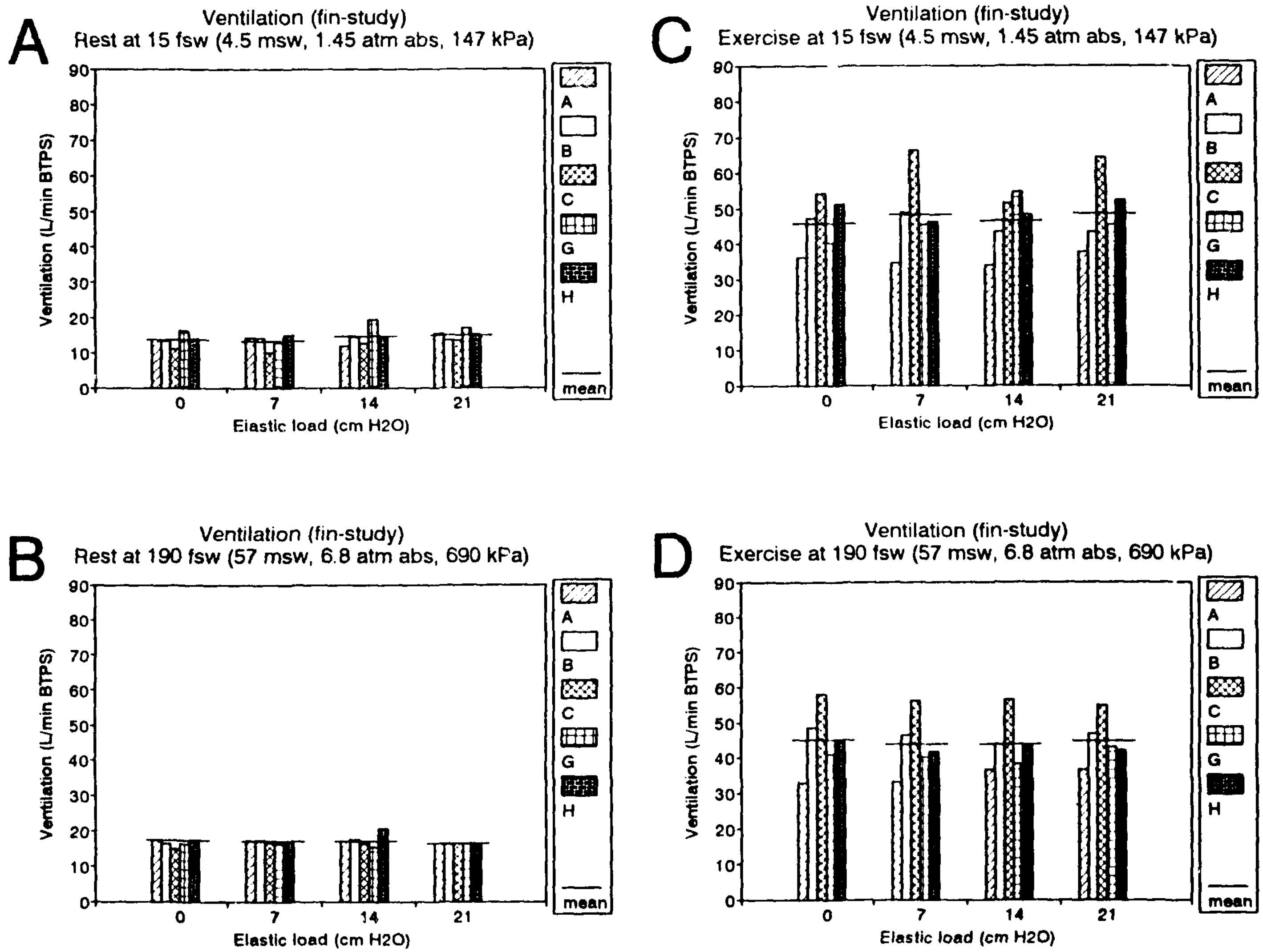


Fig 13 Ventilation ($\dot{V}_E$) plotted for the different elastic loads during fin swimming. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

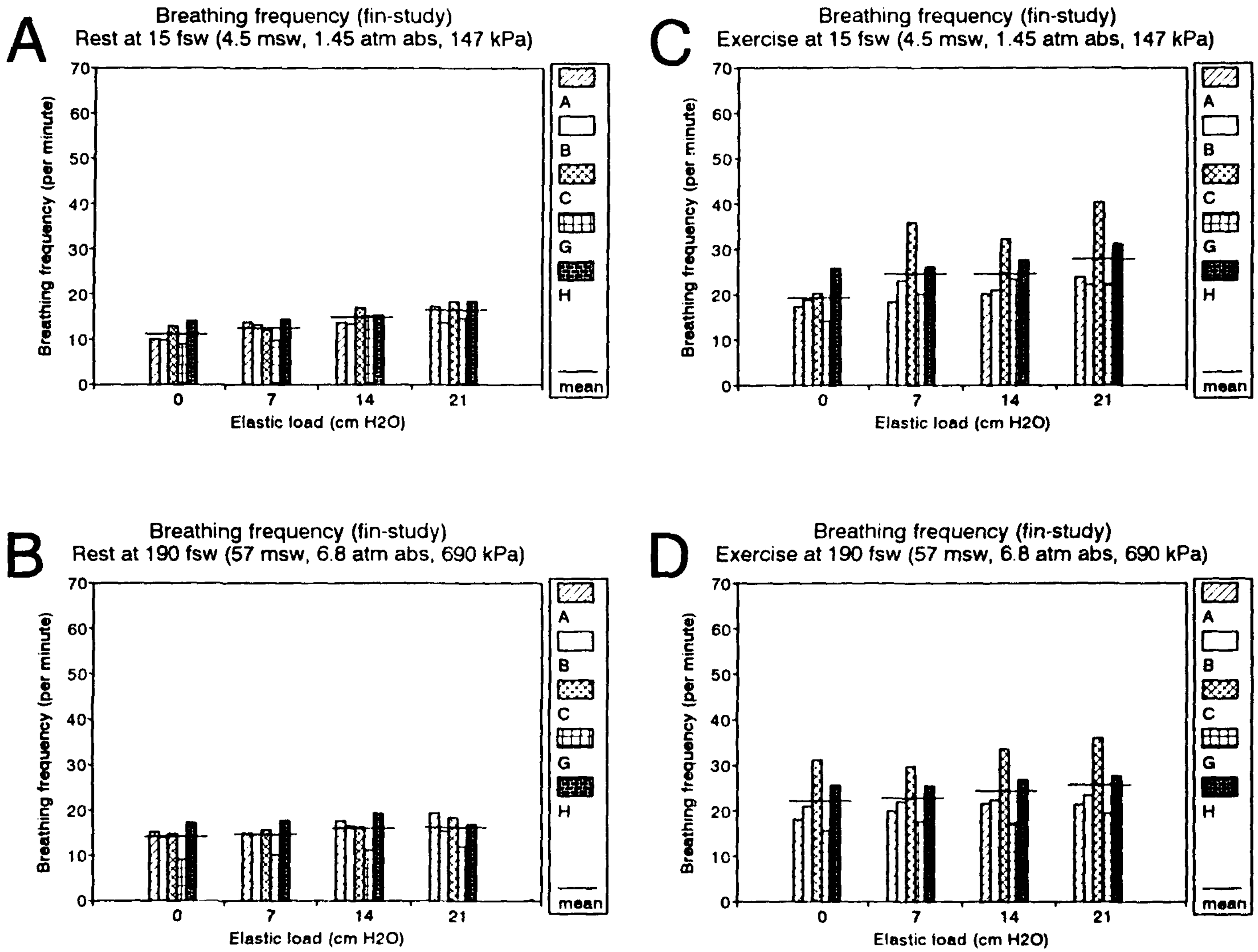


Fig 14 Breathing frequency plotted for the different elastic loads during fin swimming. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

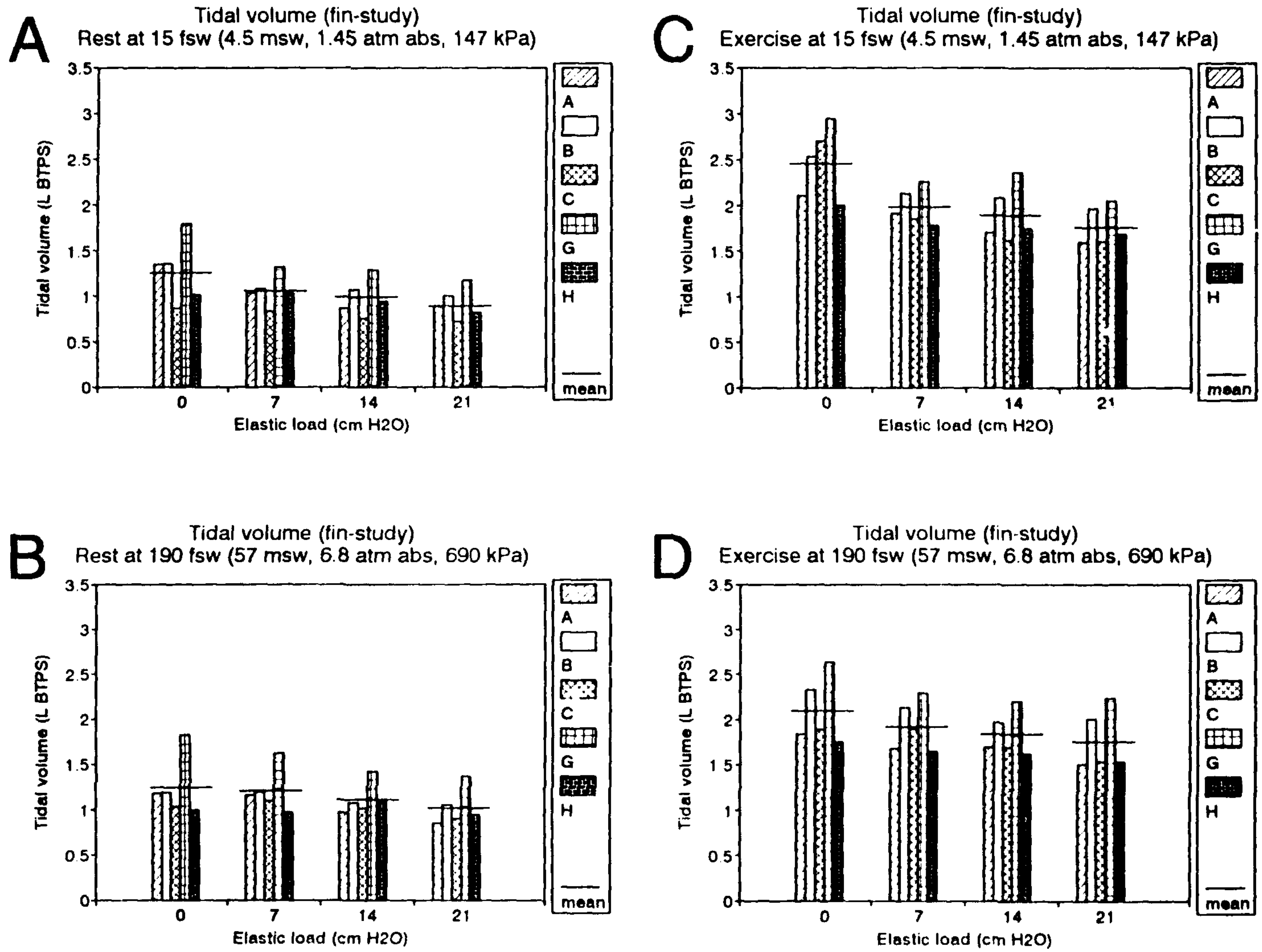


Fig 15 Tidal volume plotted for the different elastic loads during fin swimming. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

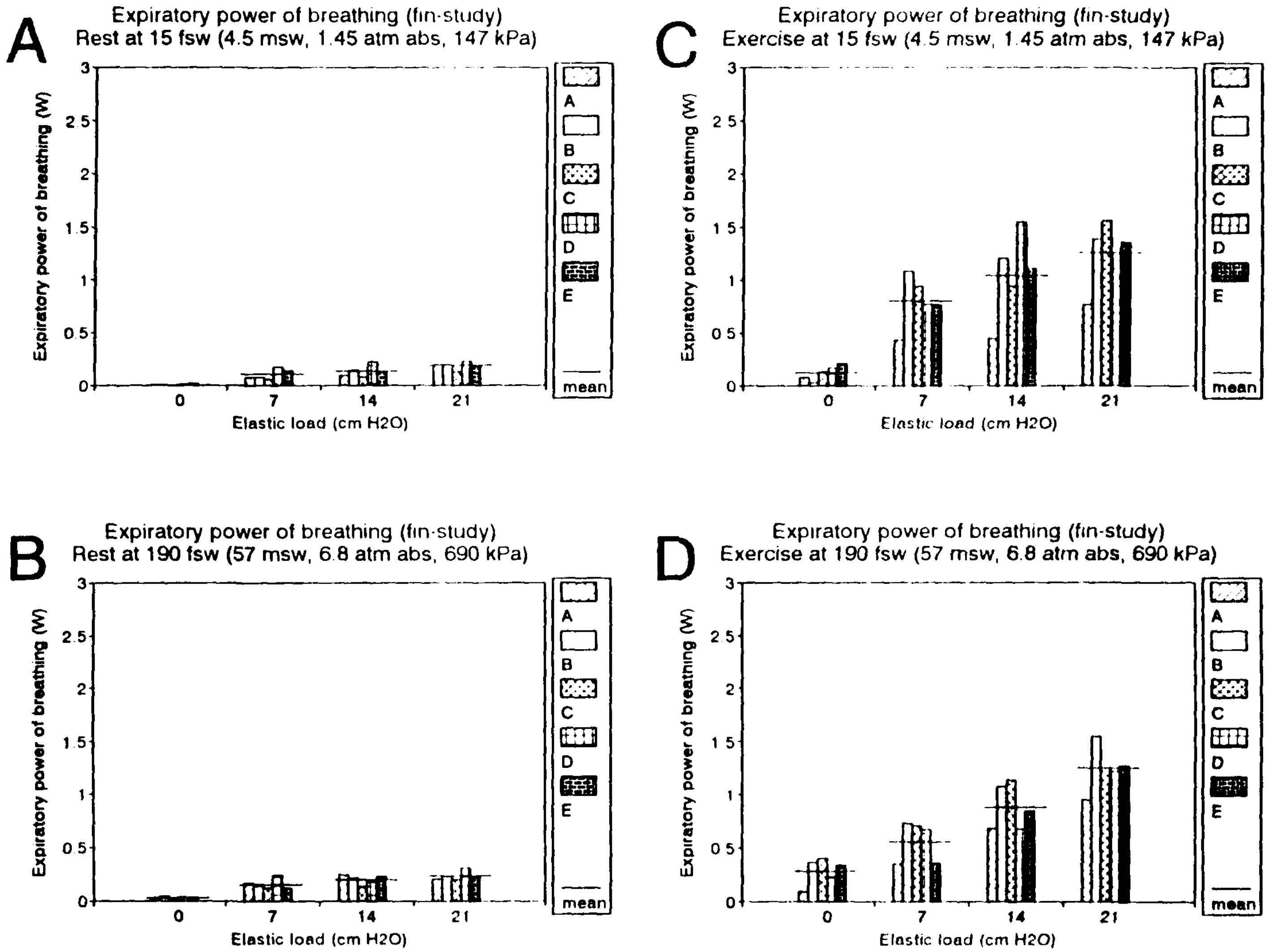


Fig 16 Expiratory power of breathing plotted for the different elastic loads during fin swimming. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

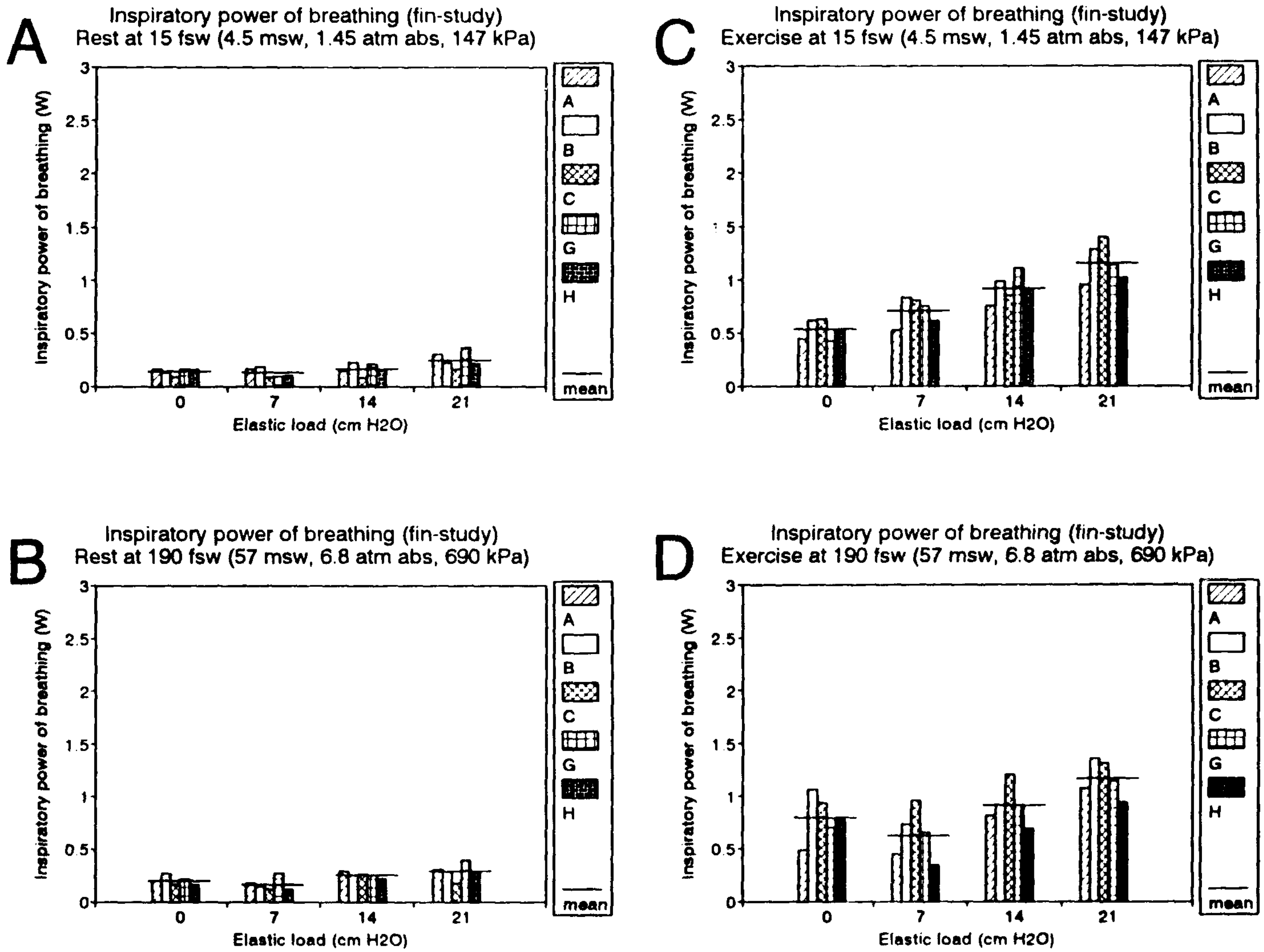


Fig 17 Inspiratory power of breathing plotted for the different elastic loads during fin swimming. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

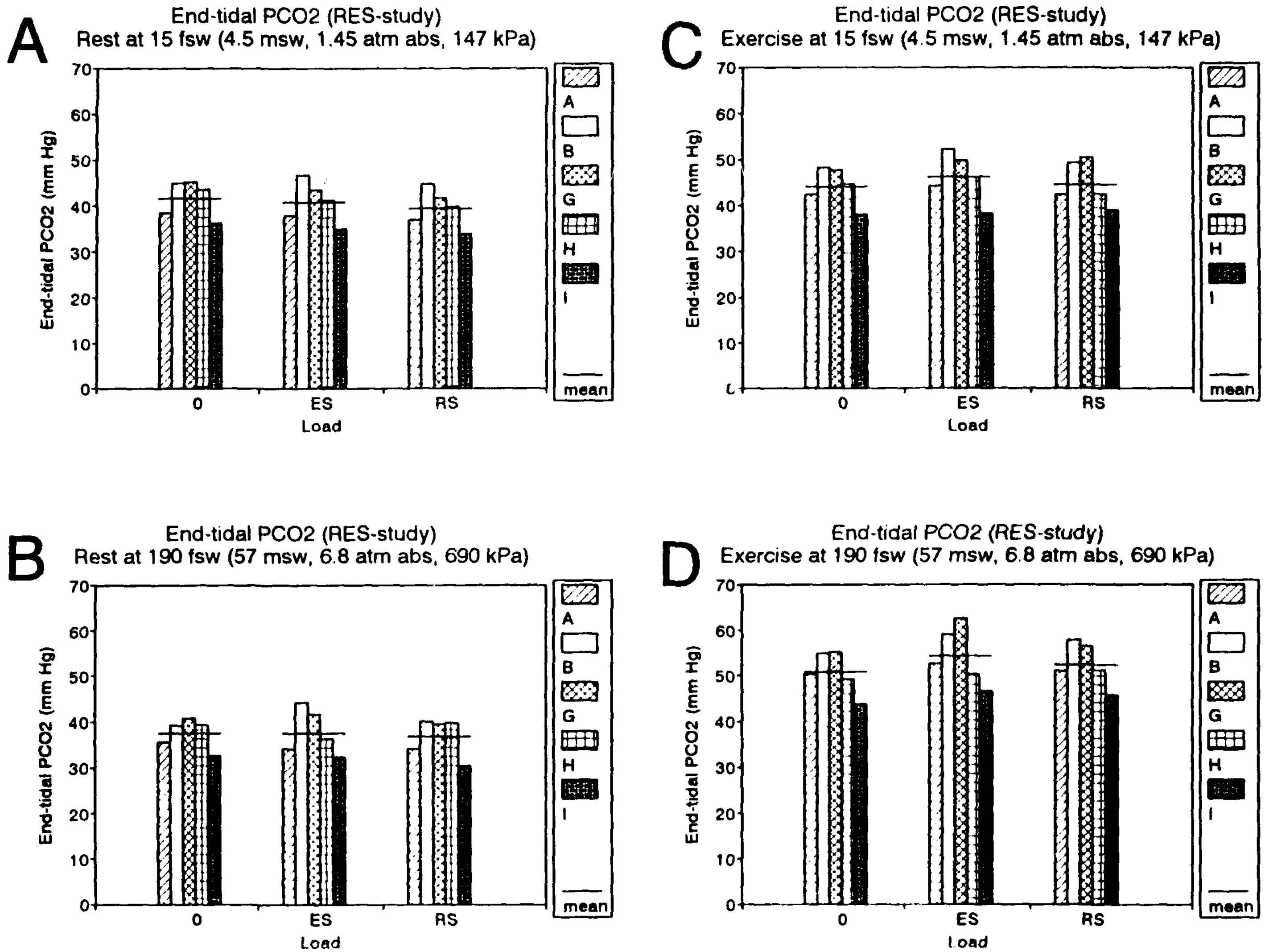
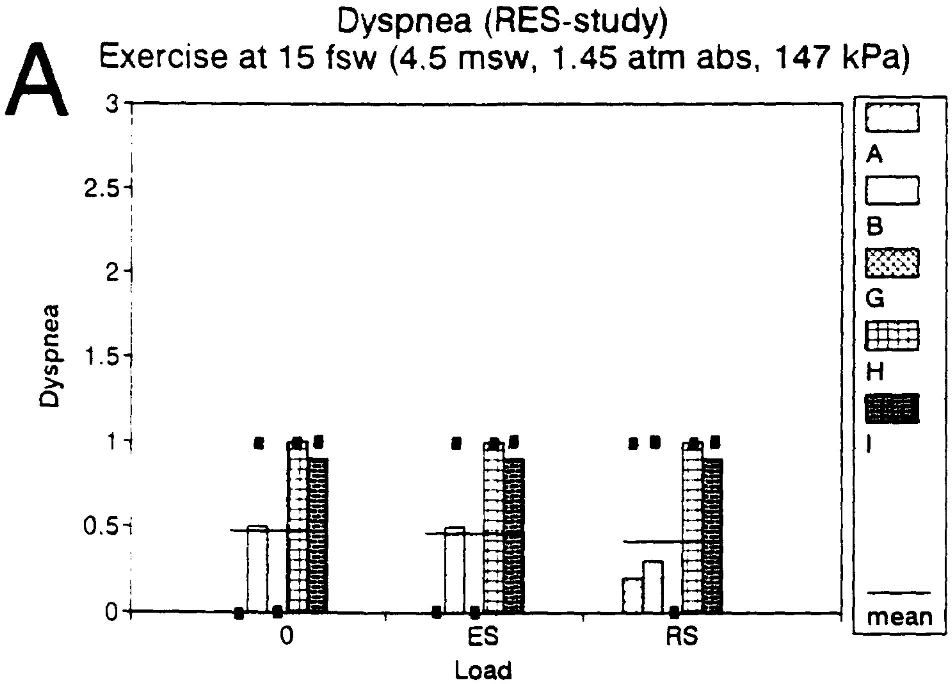


Fig 18 End-tidal CO_2 plotted for the different load combinations during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.



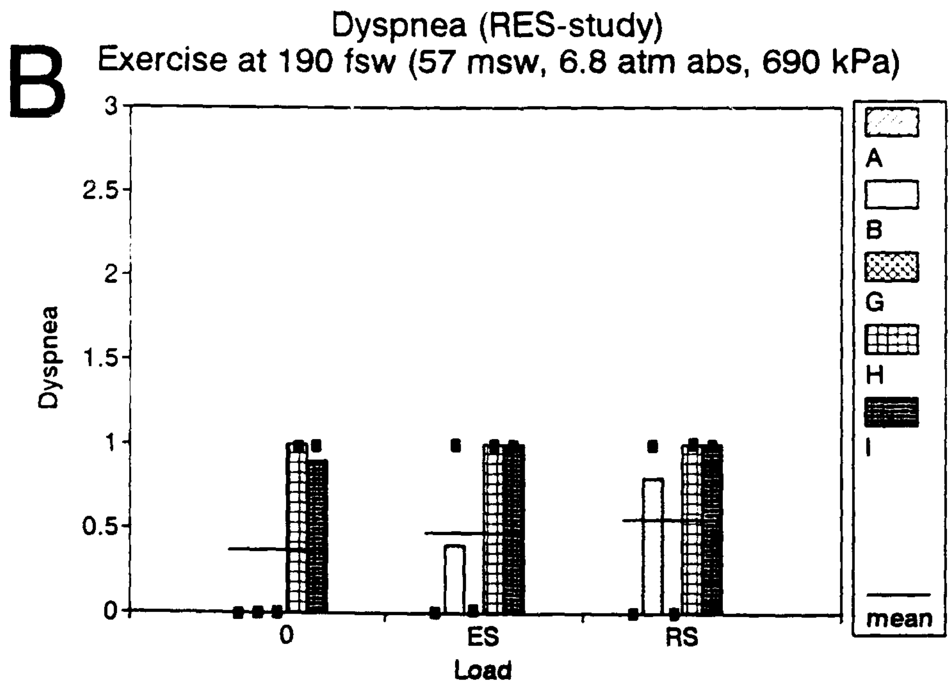
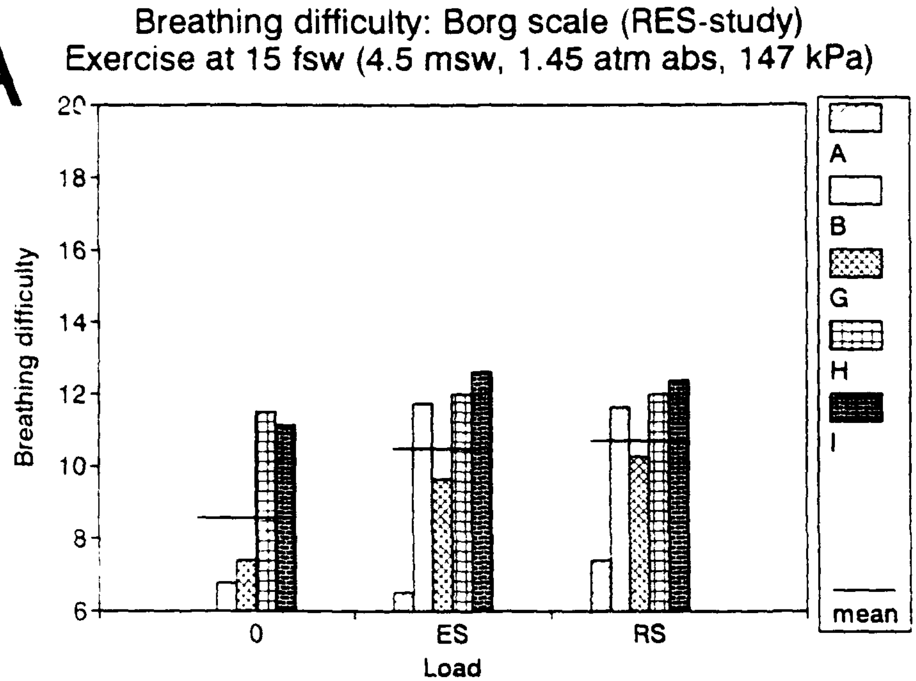


Fig 19 Dyspnea scores plotted for the different load combinations during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean, dots indicate the highest score reported by each subject. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

A



B

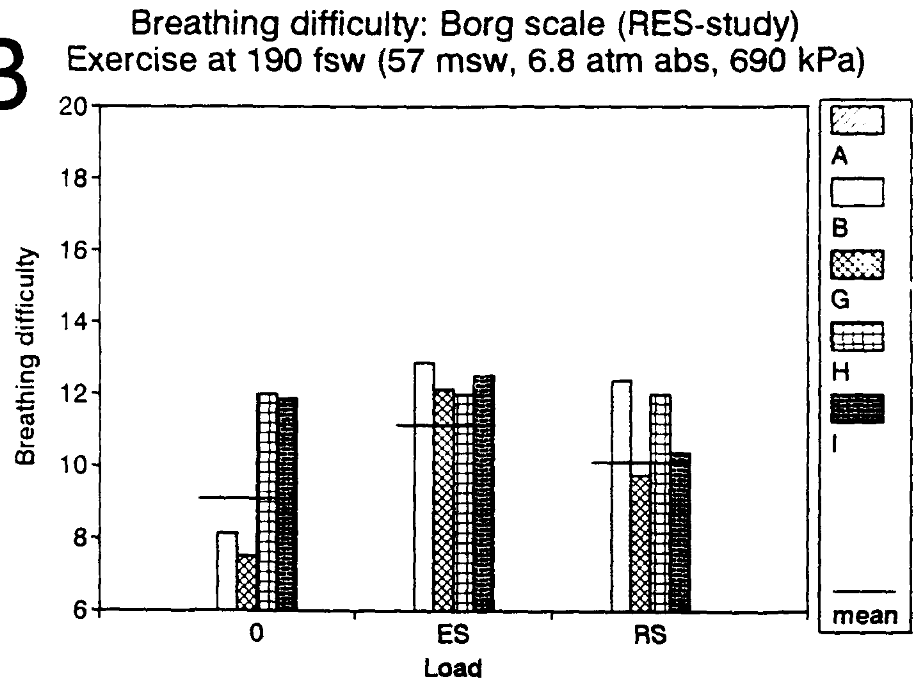


Fig 20 Breathing difficulty (Borg-scale) plotted for the different load combinations during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

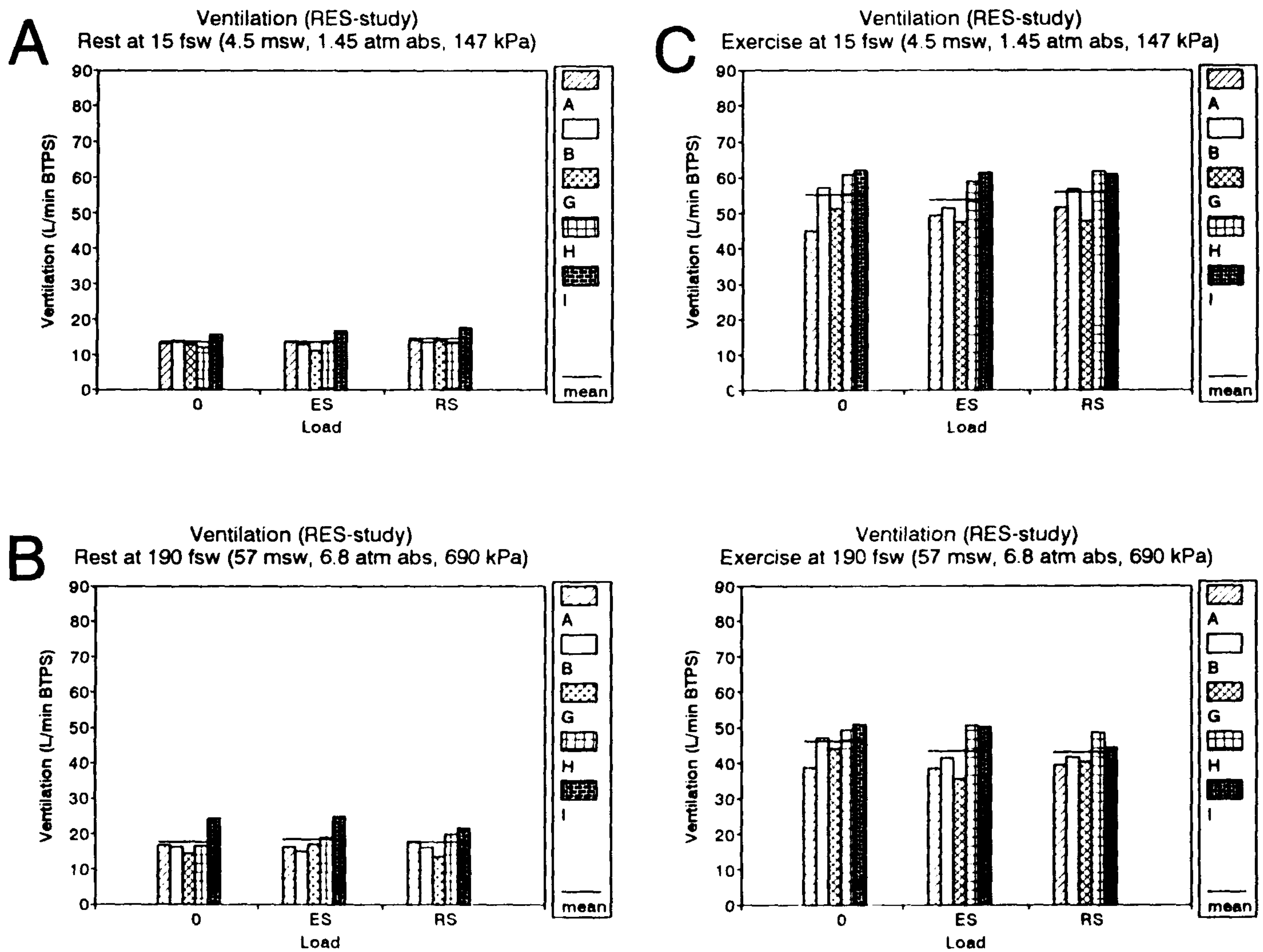


Fig 21 Ventilation (V_E) plotted for the different load combinations during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

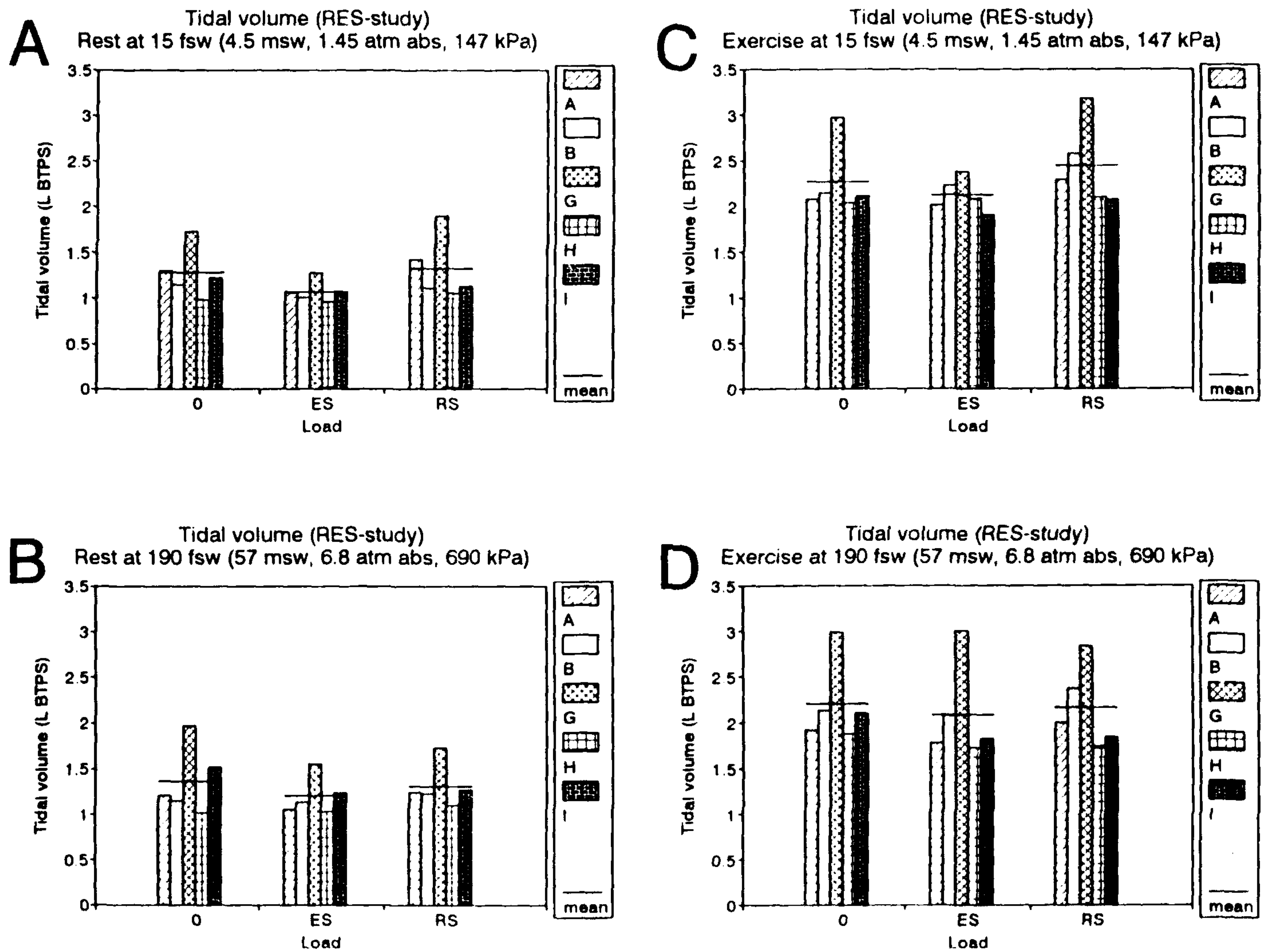


Fig 22 Tidal volume plotted for the different load combinations during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

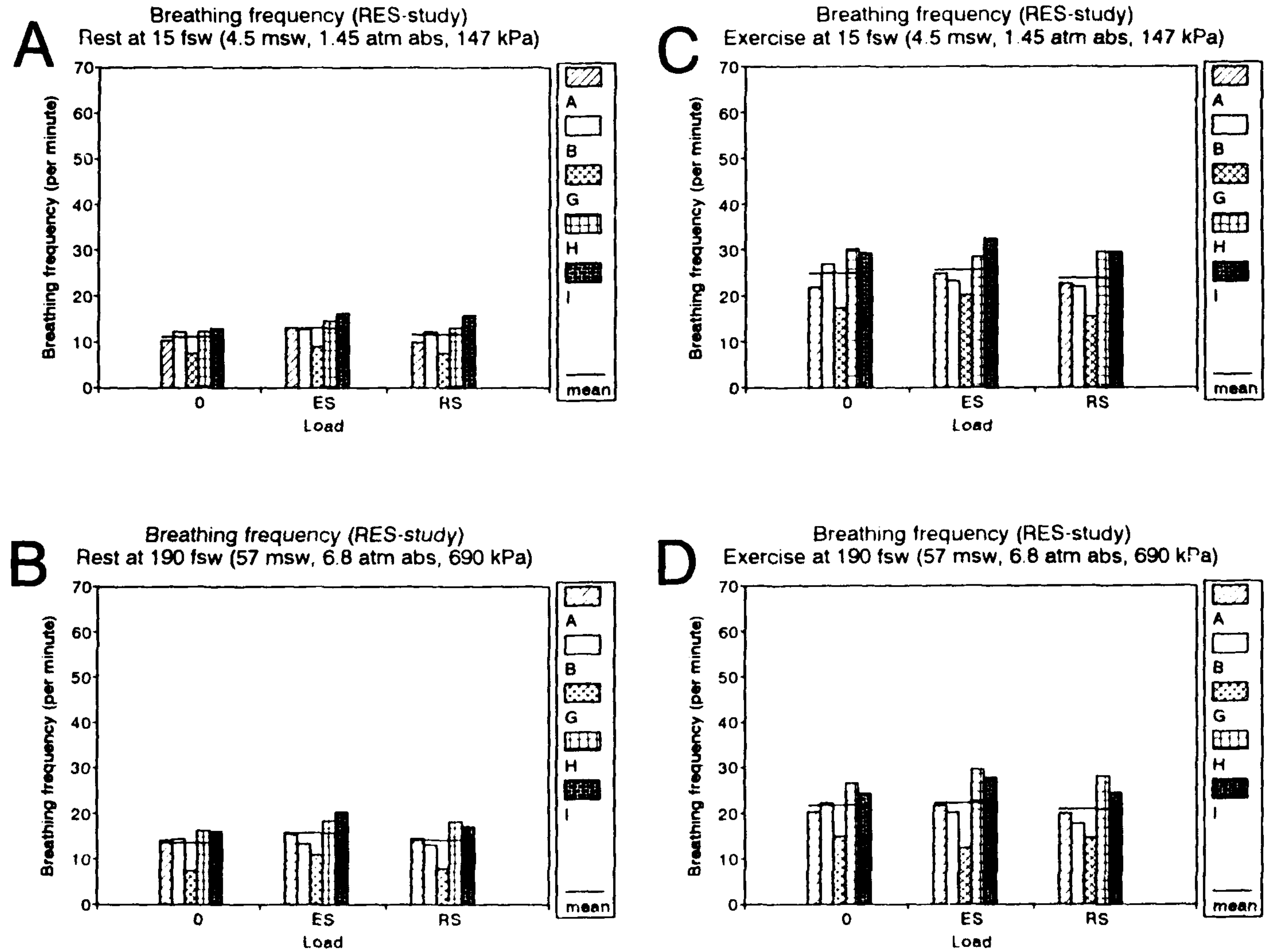


Fig 23 Breathing frequency plotted for the different load combinations during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

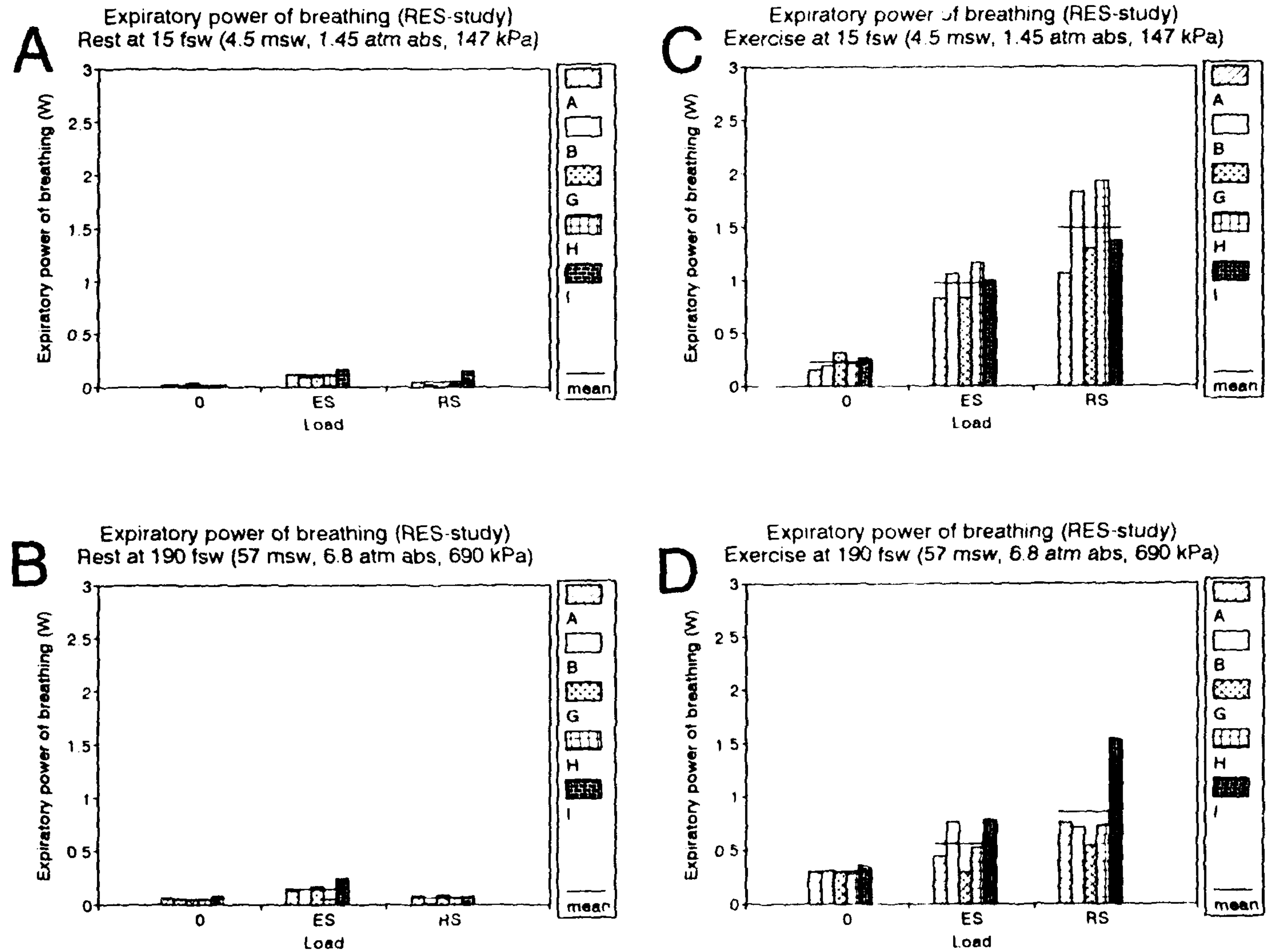


Fig 24 Expiratory power of breathing plotted for the different load combinations during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the shallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

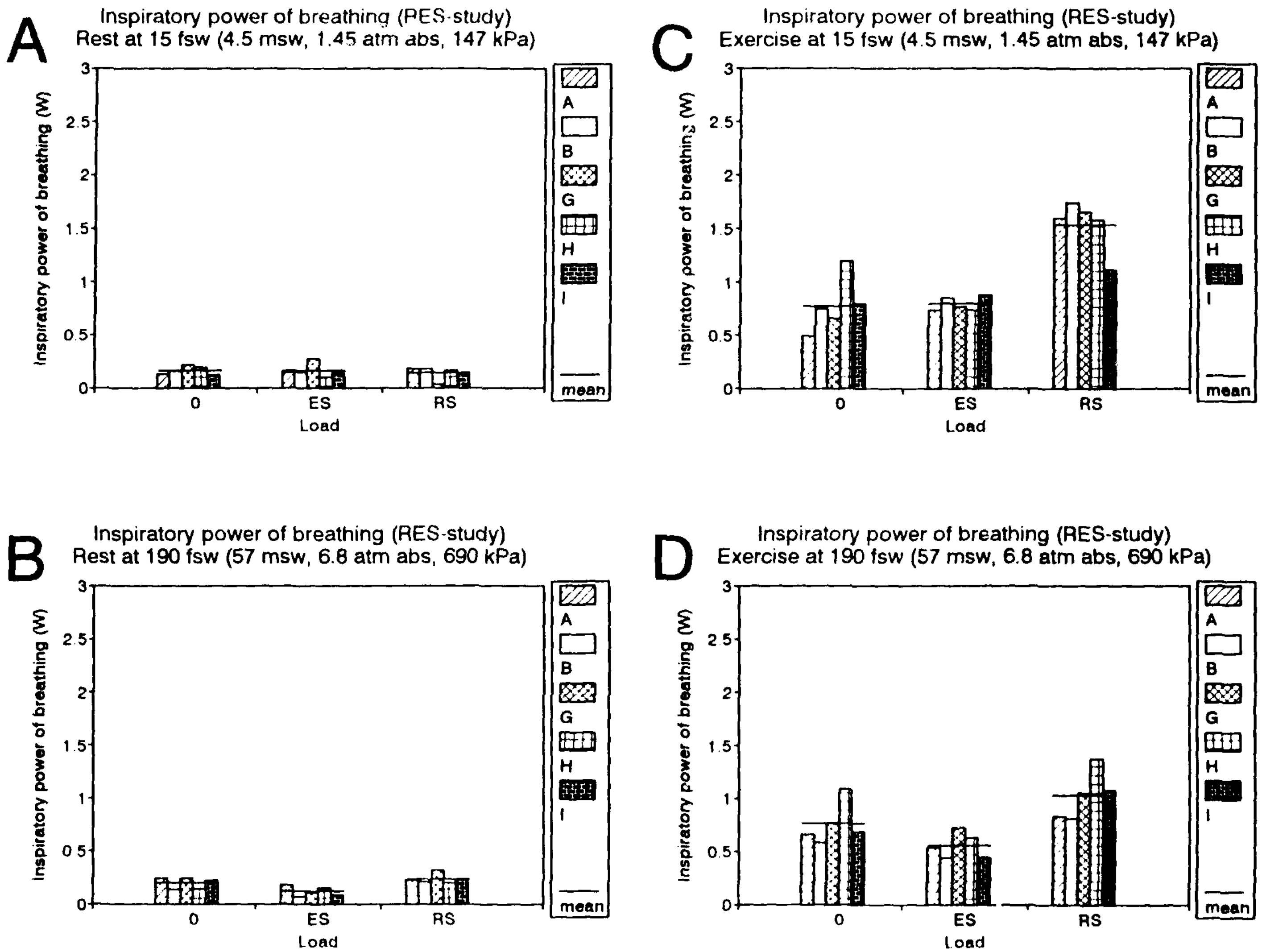


Fig 25 Inspiratory power of breathing plotted for the different load combinations during ergometer exercise. Each bar represents one subject, the horizontal line shows the group mean. Panel A: data from rest at the snallow depth, panel B: rest at the greater depth, panel C: exercise at the shallow depth, panel D: exercise at the greater depth.

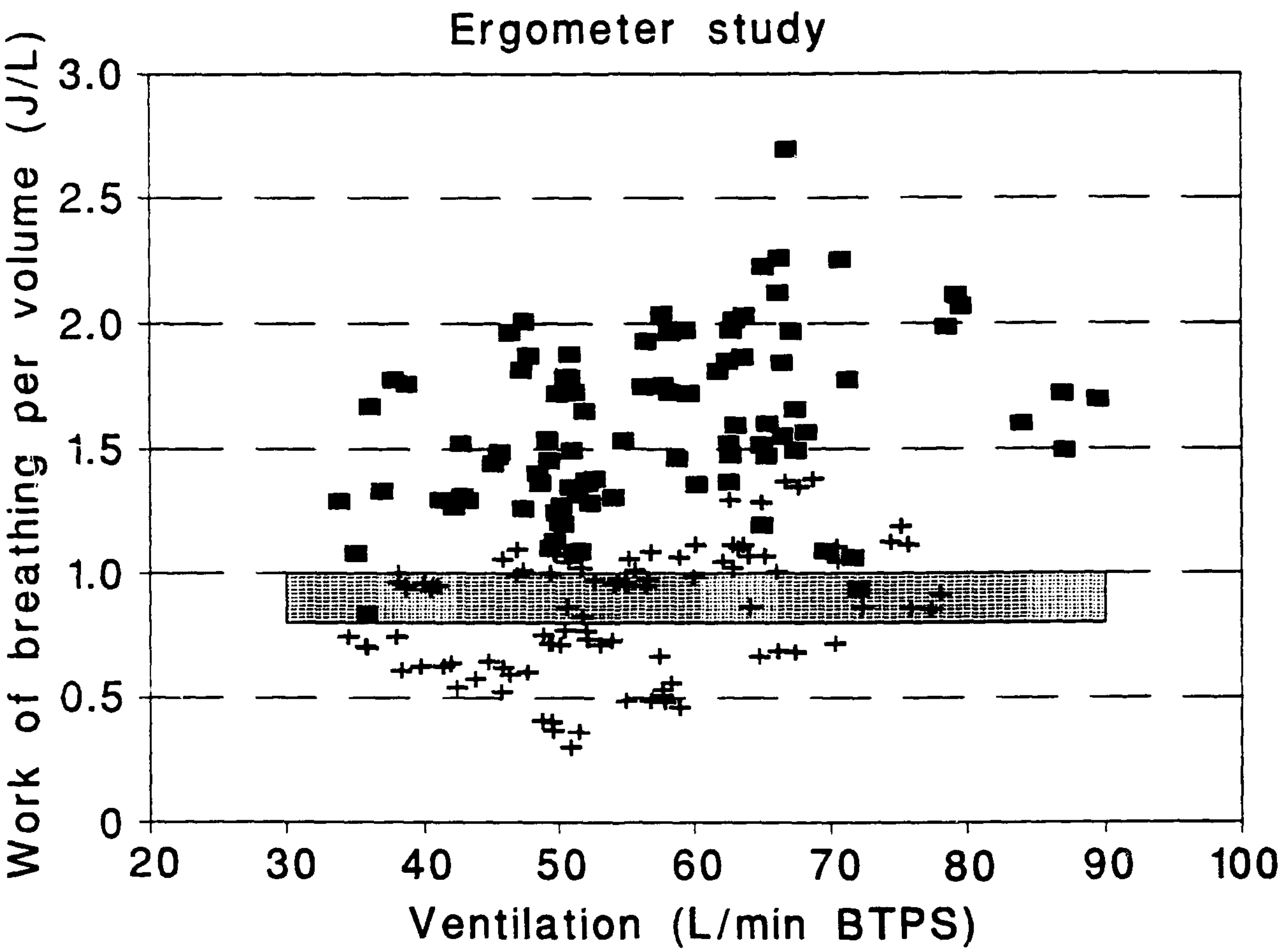


Fig 26 Work of breathing per volume (volume averaged pressure) plotted against ventilation ($\dot{V}_E$). Data from both depths during ergometer exercise. For interpretation, see text.

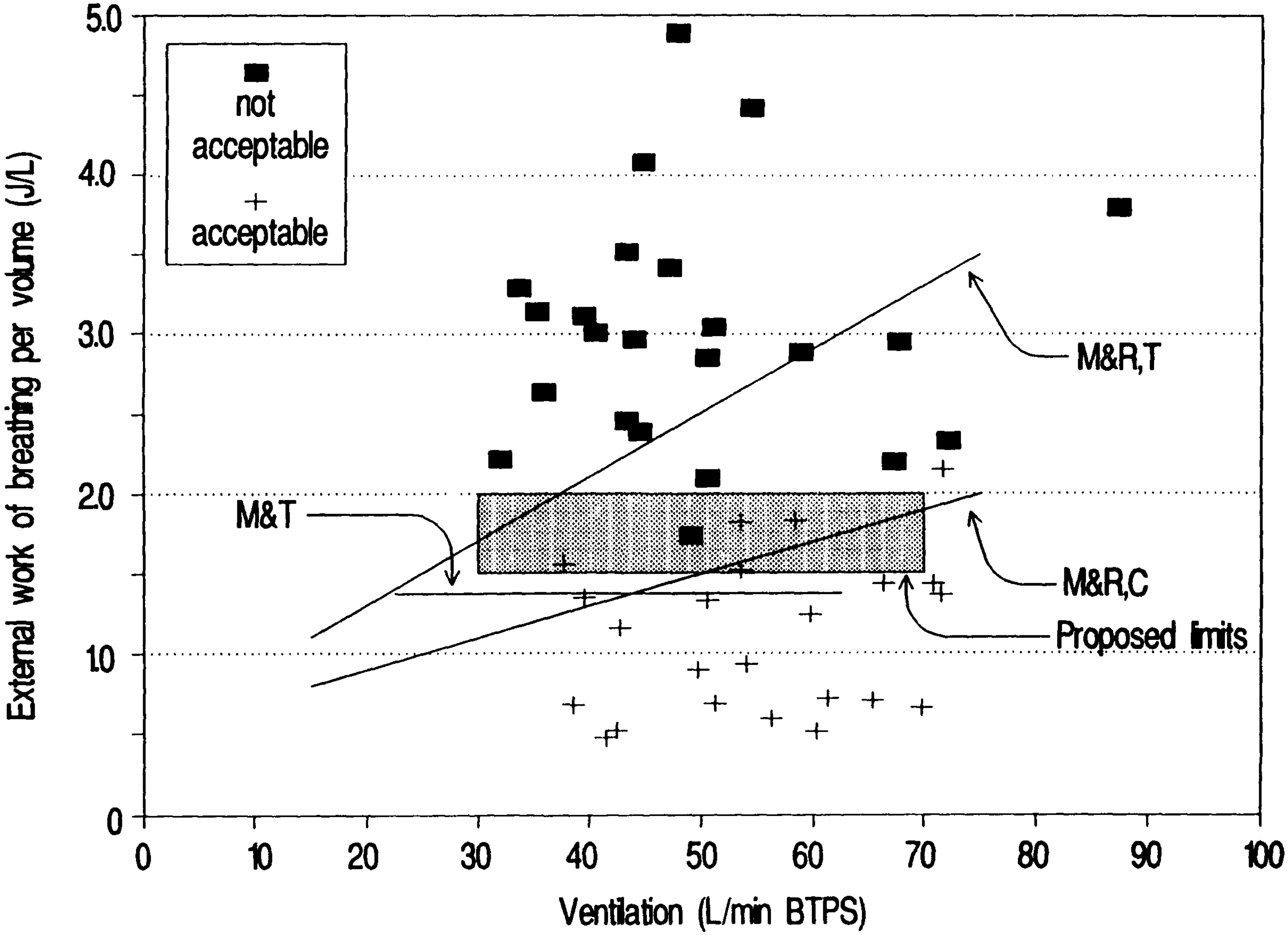


Fig 27 External work of breathing per volume (volume-averaged pressure) plotted against ventilation ($\dot{V}_E$) during an earlier resistance study (Warkander & Lundgren, 1992B). M&T shows the acceptability limit as defined by Middleton and Thalmann (1981). M&R,C shows the comfort limit as defined by Morrison and Reimers (1981), and M&R,T shows the tolerance limit as defined by the same authors. The shaded area shows the proposed limits based on our data in that study.

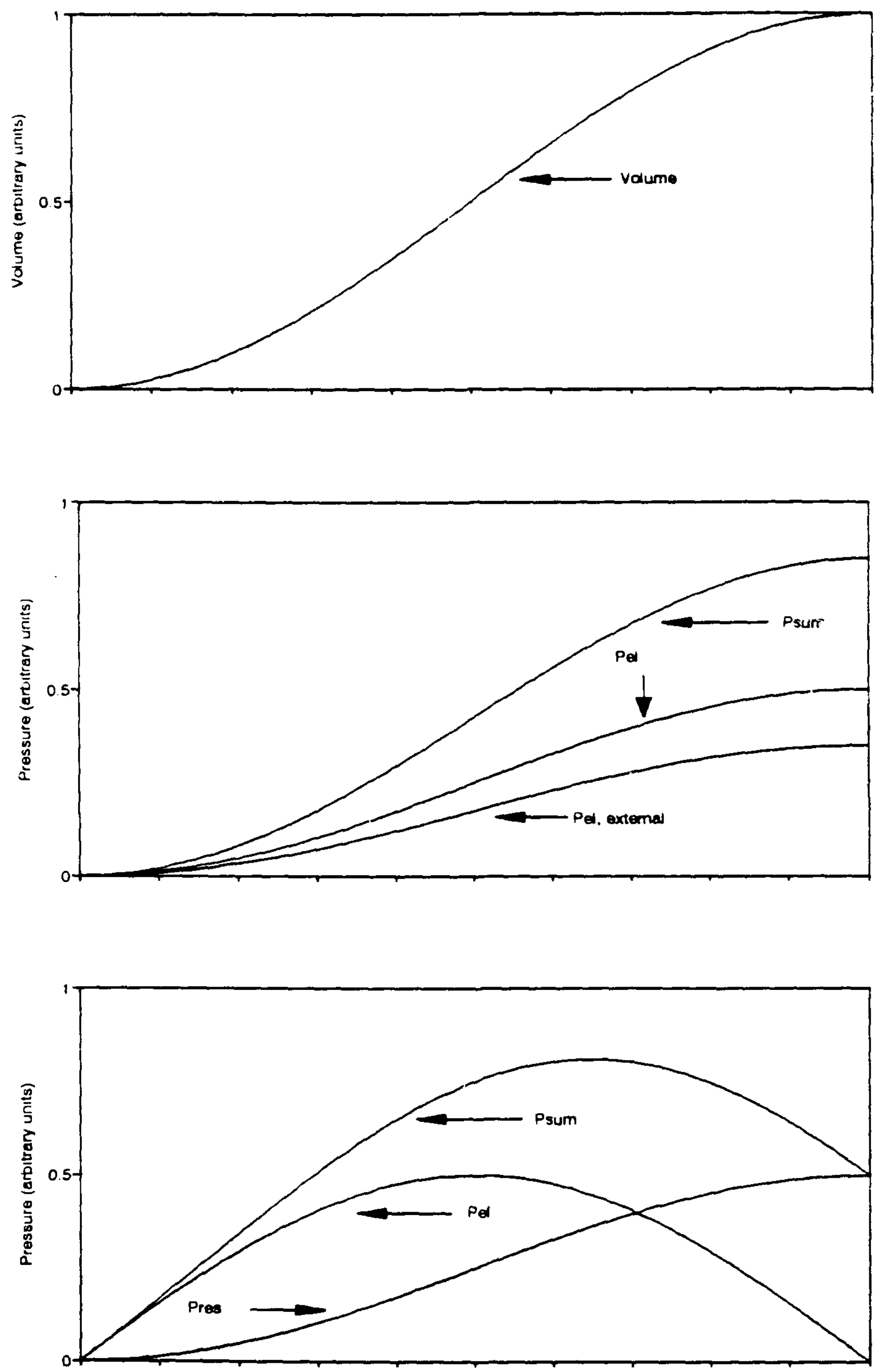


Fig 28 The different pressure components during a sine-wave shaped inspiration. Top panel shows the inspiration. The middle panel shows the pressures exerted against the elastance of the chest and lungs (Pel) and an external elastance (Pel,external), Psum shows the sum of these two pressures. The bottom panel shows the pressures exerted against the elastance of the chest and lungs (Pel) and an external resistance (Pres). Psum shows the sum of these two pressures. Note that the peak P_{sum} in the middle panel (external elastance) is reached at the largest lung volume (insp. muscles at a disadvantage).

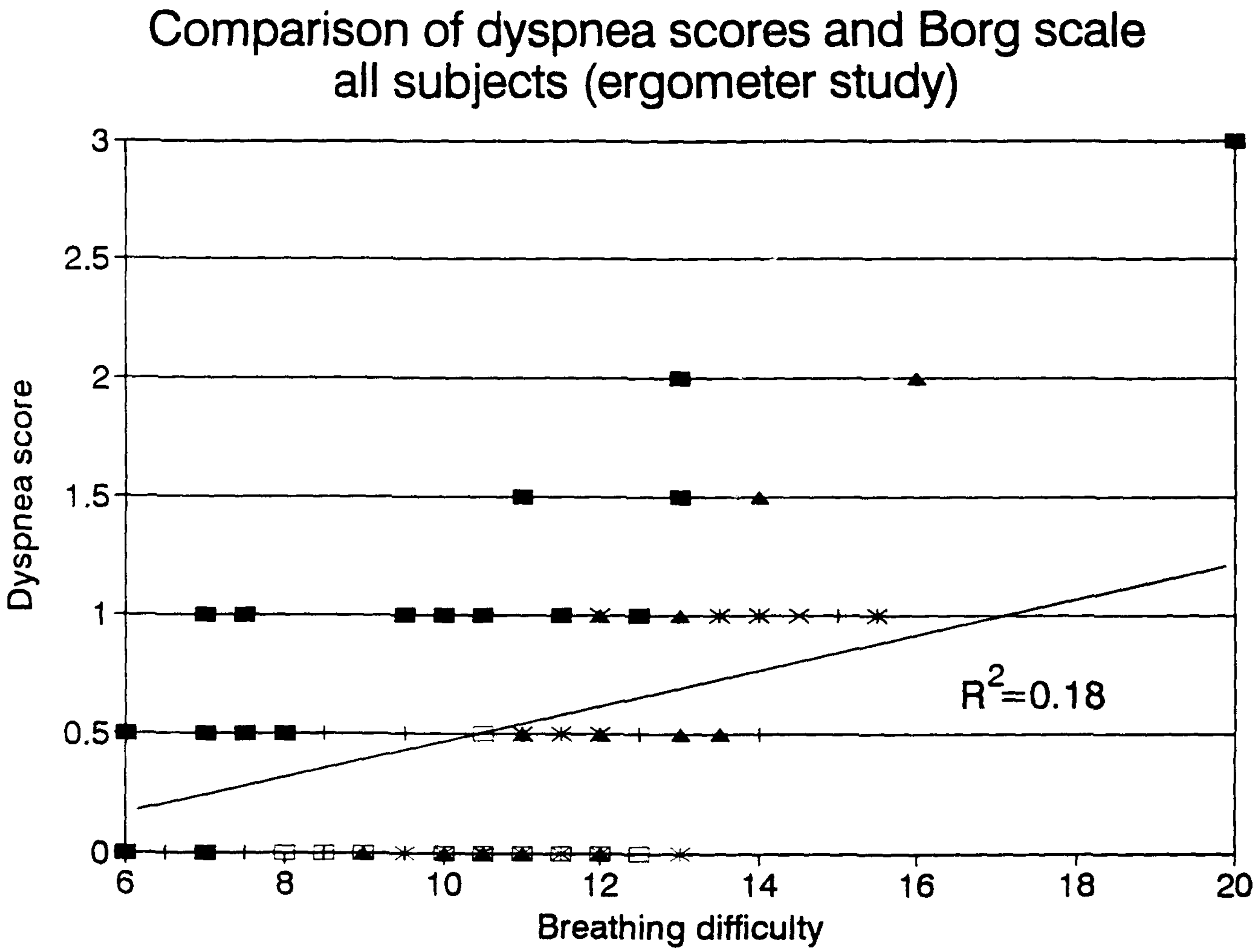
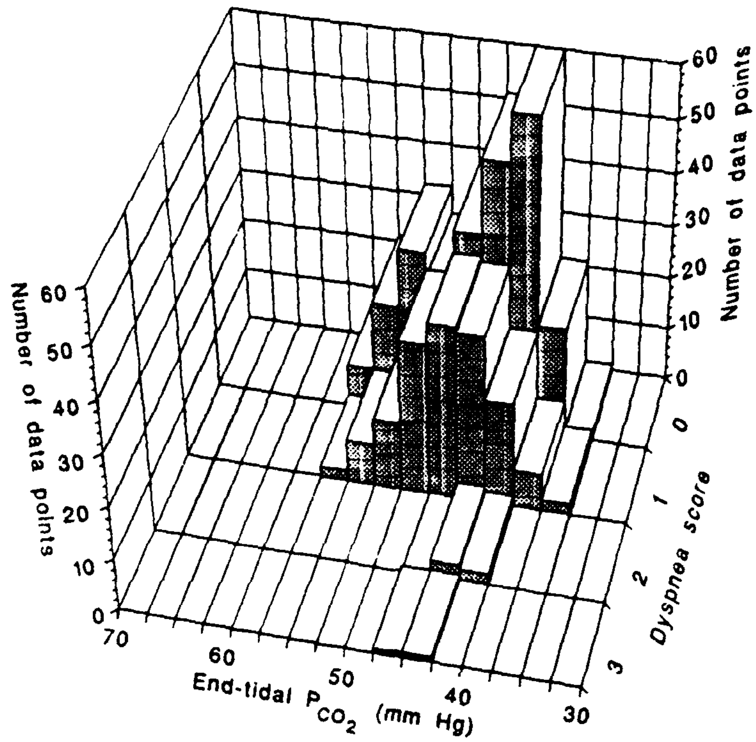


Fig 29 Comparison of the scale for dyspnea scores and the Borg-scale. See text for interpretation.

Ergometer, fin and RES studies

Exercise at 15 fsw (4.5 msw, 1.45 atm abs, 147 kPa)



Exercise at 190 fsw (57 msw, 6.8 atm abs, 147 kPa)

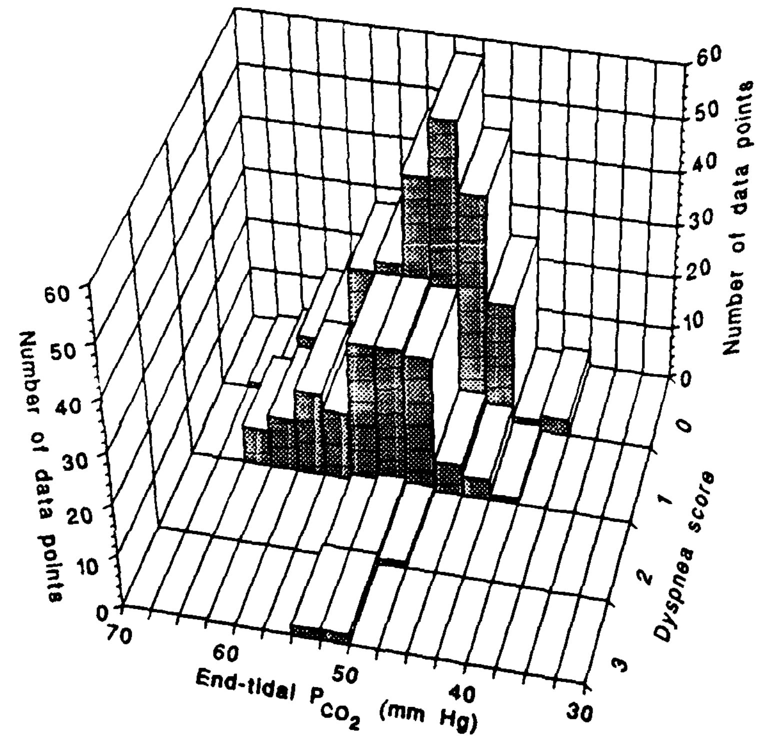


Fig 30 A 3D-diagram showing the number of data points for combinations of dyspnea scores and end-tidal CO_2 values. Data obtained from all experimental conditions except rest. The top graph shows data from the shallow graph and the bottom graph shows data from the greater depth. Note that high dyspnea scores occurred with relatively low PCO_2 values and vice versa.